

# **Simulation to Assess Plumbing and Fire Protection Innovations**

by

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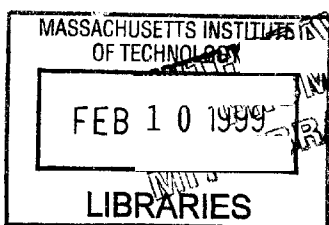
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## **ABSTRACT**

Computer-based models that simulate the installation of plumbing and fire protection systems are developed and used to assess the impacts of innovations and design changes on the installation processes. The dynamic process models simulate the activities associated with the installation processes at the specific task level, allowing for improved responsiveness to changes in the process flow, project specifics, or project dynamics for a particular installation project. Detailed information pertaining to the models was gathered through literature, construction site visits, and interviews with industry professionals. From this information, process flow diagrams were developed to formally characterize the plumbing and fire protection installation processes. These flow diagrams were then incorporated into SIMPROCESS®, commercially available software that served as the simulation environment. Plumbing and fire protection systems for a prototype building were designed, and project specific information related to the designs was used to test the validity, reliability, responsiveness, and accuracy of the computer models. The models were then used to evaluate the potential cost, time, and safety impacts of four recent innovations: flexible piping systems, grooved pipe fittings, Gravity-Film-Exchange (GFX) systems, and Sovent® aerators. The simulation models indicate that the innovations, with the exception of the GFX system, can significantly reduce the time and direct labor costs associated with plumbing or fire protection installation while simultaneously improving worker safety. The GFX system requires slightly more time to install than traditional systems, but its potential improvements on system performance may outweigh the additional installation costs. The combination of three innovations (grooved fittings, the GFX system, and Sovent® aerators) showed significant cost and duration savings, far above any one of the innovations singly. The completed models represent a new methodology for simulating plumbing and fire protection installation, thus providing owners, designers, and contractors with a unique and flexible tool for analyzing alternatives accurately and quickly.

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# 1 Introduction

## 1.1 Research Objectives

The overall objective of this research is to develop dynamic process models for simulating the installation of plumbing and fire protection systems to evaluate the impact of innovations and design changes on the installation processes (Carr, 1998). The computer-based models represent a completely new methodology for simulating the installation processes, and, as a result, provide owners, designers, and contractors with a unique and flexible tool for analyzing alternatives accurately and quickly.

The plumbing and fire protection industries have generally relied on “traditional” methods like the Critical Path Method and the Quantity Take-Off Method for planning and estimating an installation project (Dowd, Valante, 1996). These “top-down” methods of planning first approach a project at its most general level, and then group materials and general activities in a hierarchical fashion until a certain level of detail is reached. The traditional tools are useful in identifying the general activities and material requirements associated with a project, but they do not explicitly recognize the most detailed tasks that make up the installation process. The plumbing and fire protection simulations presented here approach the planning process from a different perspective - they characterize the processes from the most detailed level of tasks. In evaluating a particular design change or alternative, this detailed approach helps to pinpoint the installation implications, and provides a better understanding of the degree to which certain plumbing and fire protection tasks are affected.

In order to develop responsive, accurate, and reliable computer models, the installation processes must be clearly understood. Naturally, the more a process is understood, the better it can be improved. The characterization of the processes helps to identify the most prevalent and repetitive tasks involved with the process in order to determine where changes can have the most effect on the overall process. Conversely, potential vulnerabilities to “bottlenecks” can be identified through characterization as well. Lastly, characterization helps to identify and understand the design attributes of a building that have the most significant effects on the installation process.

The model was developed in four major steps (Attai, 1997). First, research on the installation processes was conducted, and specific materials, means, and methods associated with each process were identified. Second, a general framework was developed for each process based on the research conducted. The frameworks help to characterize the specific processes applicable to virtually any plumbing or fire protection system for any building. Third, the frameworks were used to generate computer models that could be used to simulate installation. Finally, plumbing and fire protection

systems were designed for a “prototype” building, and the computer models were used to simulate the installation of these systems.

## **1.2 Research Significance**

The research presented here can have significant implications in improving the efficiency of the construction of facilities (Slaughter, 1997). By providing a flexible means of assessing new technologies, the existing barriers to the applications of these innovations can be lowered. Owners, designers, and contractors will be able to develop and evaluate design and installation alternatives with greater ease and improved confidence. This reduction in perceived risks will encourage a more rapid implementation of innovative ideas.

The entire value system associated with the plumbing and fire protection industries can benefit from the flexibility and responsiveness of the computer models. From the mechanical contractor’s point of view, the models will allow the contractor to evaluate the feasibility of different installation options in terms of cost, time, and safety. In addition, the contractor can use the models to identify the downstream effects of reassigning resources to accommodate an installation change. A plumbing or fire protection designer can use the models to evaluate the effects of various system and material alternatives on the cost of installation. Project managers can identify the “ripple” effects that a change in one system may have on the progress of other building systems during the construction process. The additional accuracy in planning for alternatives and innovations will ultimately result in reduced risk for the owners, and will allow owners to incorporate the best products into their buildings.

The process models are not intended to replace traditional methods of estimating and scheduling projects. Rather, they are meant to serve as supplementary tools that enable planners to ask “What if?” By approximating field conditions, planners will be able to develop and evaluate new ideas without having to dedicate the costs and time associated with full-scale experimentation.

## **1.3 Background**

The multiplicity of variables in construction presents a significant barrier to innovation in the construction industry. Owners, designers, and contractors are often faced with a great deal of uncertainty and risk, especially with new designs and innovative technologies (Slaughter, 1997). In addition to the duration and cost issues associated with an innovation, the implications of the innovation must be addressed with regards to regulatory, safety, and technical constraints. Unfortunately, most construction

industry members do not have the financial luxury to conduct full-scale experiments in their assessment of innovative technologies or designs (CITE?). As a result, potentially superior (in terms of cost, time, safety, performance, etc.) ideas may never be implemented.

To address these problems, project teams need a system that can assist them by making it possible to generate and analyze a range of courses of action and their likely outcomes in an accurate and economical way (Ndekugri & Lansley, 1992). Many construction officials believe that computer-based simulation models can provide this system.

A current research program at the Massachusetts Institute of Technology, under the direction of Professor Slaughter, is currently developing computer-based process simulation models that will allow rapid and accurate formulation of a construction procedure by focusing on the detailed components of the process (Slaughter, 1997). The dynamic process models operate on a microcomputer and are based upon data collected from industry participants and on-site observations.

To date, models have been completed for three construction-related areas: structural steel erection, exterior enclosure, and cast-in-place concrete construction. Additional models are being developed for Heating, Ventilation, and Air conditioning (HVAC) system installations, interior finish work, and electrical work. These models, in combination with the plumbing and fire protection installation models developed here are designed to fit into a “meta-model” that simulates the entire set of processes associated with building construction.

## **1.4 Thesis Organization**

Chapter 2 summarizes traditional planning tools used in the construction industry, including the Critical Path Method (CPM) and the Quantity Take-Off Method, and discusses the need for more accurate and detailed simulation models. The advantages and disadvantages of three types of simulation models (queuing, graphic-based, and dynamic process models) are identified and compared for their applicability in simulating construction activities.

Chapter 3 is an overview of the methodology employed in this research for modeling plumbing and fire protection installation. Strategies used to characterize the process, including data collection techniques and literature reviews, are described in detail. Techniques used to verify the accuracy and responsiveness of the models are also discussed.

Chapter 4 identifies the basic principles of plumbing and fire protection systems, and outlines the processes associated with their installation. Common terms are identified, and the general framework associated with each type of installation is presented to provide a clear characterization of the process.

Chapter 5 describes the computer-based dynamic process models used to simulate the installation processes. The chapter includes a description of the computer program used for the model and a description of the systems chosen for the prototype building. The final sections of the Chapter discuss the results of the simulations run for the prototype systems.

Chapter 6 introduces and describes four recent innovations in plumbing and fire protection installation. The implications of each innovation are identified in terms of their impacts on process flow, project specifics, and project dynamics. A computer simulation is run for each innovation, and the results are compared with the traditional prototype system described in Chapter 5.

Chapter 7 presents a summary of the research described in this thesis. Possible future applications of the process models are identified and discussed, and suggestions for further research are offered.

## **2 Background**

The multiplicity of variables inherent in construction creates a need for flexible tools to assist decision-makers during all phases of a project. Traditional planning tools like the Critical Path Method (CPM) and the Quantity Take-Off Method are useful for general cost and duration assessments, but they fail to capture the complex interactions among various pieces of construction including resources, materials, and site conditions. Simulation, which is defined as “the accurate representation of actual processes” (Slaughter, 1997), is necessary to accurately predict the impacts of any design or construction decision.

This chapter summarizes traditional planning tools like CPM and the Quantity Take-Off method, and then compares recent advancements in construction simulation models.

### **2.1 Traditional Estimating Tools**

#### **2.1.1 Quantity Take-Off Method**

In estimating the cost and duration of a plumbing or fire protection installation, mechanical contractors typically rely on various forms of the Quantity Take-Off Method (Dowd, 1998). Popular variations include the Unit Cost method and the Labor Hour approach (Ibbs, 1997).

The Unit Cost Method relies on published data that assigns a cost to a particular unit of material. In plumbing for example, the unit of material may be a linear foot of pipe, or a particular type of fixture. The cost per unit includes labor, material, and indirect costs. Contractors simply determine the total number of units of material required for a particular job, and multiply the total by the unit cost. Contractors either maintain their own database of unit costs, or they use published unit cost data books like R.S. Means Mechanical Cost Data books (1997).

The Labor Hour approach is similar to the Unit Cost Method, but contractors assign labor hours to a particular unit of material instead of cost. Labor hours are then summed for the total number of various units, and the total cost is derived by multiplying the total labor hour requirement by the prevailing wage rate.

The quantity take-off method is a useful estimating tool for determining material costs, but it is not flexible enough to accurately predict labor requirements. The method assumes that labor

requirements are constant. In reality, site conditions and design specifics have a significant impact on labor requirements and installation times for both plumbing and fire protection systems.

### **2.1.2 Critical Path Method**

The Critical Path Method (CPM), originally developed at Remington Rand and Dupont in the 1950's, is a useful tool for estimating the overall duration of a project. The method arranges processes in a sequential manner, and the durations of the individual processes are added to generate a project schedule.

Though widely used as scheduling tool, CPM is not a flexible or accurate simulation tool. The deterministic and static nature of CPM presents limitations in modeling the stochastic and dynamic nature of construction activities (Sawhney and Abourizk, 1995). CPM also fails to address the concept of failure or rework in construction, because cycling or feedback within a process is not allowed. Resources are not explicitly required in CPM, and so their true effect on construction duration is not accounted for.

## **2.2 Simulation Modeling**

Traditional tools have proven to be inflexible in assessing design and process alternatives in a detailed manner (Ndekugri and Lansley, 1992). For example, Sawhney and Abourizk (1995), in their development of a "Hierarchical-Simulation-Model (HSM)" for construction, identify a three-level hierarchy of planning required for a project. The first level, called the project level, requires general scheduling and cost estimating. At the second level, the operations level, tasks are broken down into systems (foundation work, plumbing) and general tasks are planned within the systems. This is usually the level of detail that is planned for prior to construction, and CPM and the Quantity Take-Off method suffice at the first two levels. However, a third level, the process level, could help to plan projects more accurately by simulating the specific tasks and resource allocations required at the unit level. At this level, simulation models can address the process to the level of detail necessary to evaluate design specifics as well as method alternatives. These simulation models will provide a more accurate estimation of the cost and duration impacts of various design and construction alternatives.

The remainder of this section focuses on simulation modeling at the process level. The models are compared for their applicability in simulating the installation of plumbing and fire protection systems. Current simulation models can be divided into three categories: queuing models, graphically-based models, and dynamic process models.

### 2.2.1 Queuing Models

Queuing theory is defined as “the mathematical study of waiting systems” (Ndekugri and Lansley, 1992). Queuing models assume that resources flow through a series of cyclic and repetitive activities. The resources are either engaged in a process activity, or are waiting in a “queue” to enter a process activity. Queuing models also assume that the processing times of activities are based on a predetermined time distribution. Similarly, the process flow itself is fixed. The attributes of the resources entities have no effect on the processes that they are used for.

The principal concern of queuing models is resource optimization. Since the resource characteristics (e.g., number, capacity, availability) and process flows are assumed to be fixed for a particular model, users can only experiment with the allocation of resources. As a result, a model may serve to optimize resource usage for a process, but the process itself may not be optimal. Also, the dynamic effect of site and material characteristics on process activities cannot be reflected in queuing models. Plumbers, for example, must often install piping in a confined area, where HVAC and electrical runs are nearby. Obviously, the installation time in these areas is much higher than in areas where the plumber does not have any spatial conflicts with the other services. A queuing model would not be able to capture this effect on processing activities like pipe installation.

The most prevalent commercial, computer-based queuing models for construction simulation are CYCLONE and MicroCYCLONE. Developed by Professor Daniel W. Halpin at Purdue University, the models are incorporated into computer packages, and have been used in several construction simulations. Cheng and O'Connor (1993) used MicroCYCLONE to identify resource inefficiencies in piping installation. Alkoc and Erbatur (1997) used MicroCYCLONE to compare the efficiencies of cranes and pumps in the placing of concrete for building slabs and columns.

Written in FORTRAN, the CYCLONE packages provide an environment in which resources move from one activity to the next a certain number of times, based on the inputs of the user. The environment is only suited for one particular process though. If the user wishes to change the system design or allocation of resources, a new process model must be created. Shi and Abourizk (1997) improved CYCLONE's flexibility to changes in their Resource-Based-Modeling (RBM) program, where resources and small processes are grouped into “atomic models.” When building a model for a specific design, the user can select the appropriate processes from a library of atomic models. Users must still create a new network of atomic processes to respond to the specifics of a particular construction process.

### 2.2.2 Graphic-Based Models

Designers and builders tend to look at a construction project from different perspectives. Designers view a project from the perspective of the physical components of the building, whereas builders are concerned with the processes and resources required for assembly of the physical components. Graphic-based simulation models attempt to “strengthen the design/construction interface by providing a running interactive simulation of construction activities in a virtual environment” (Vanegas and Opdenbosch, 1994).

The virtual environment is used to simulate the actual movement of resources and erection of components in a 3D environment. Graphic simulation’s primary goal is to allow the user to identify problems visually, and to solve the problems in the same practical way as they would be solved in real life. Ideally, designers and builders could work together in the early planning stages to identify the logistical construction implications of various design alternatives.

To create a graphic-based simulation model, the designer must first input the design attributes of the building into a CAD program. Next, the builder must input the sequence of erection of the various physical components as specified by the designer. By incorporating the sequence of construction, time becomes a critical factor in the graphic-based model. Professor Martin Fisher at Stanford University is currently researching the effects of the logical sequence in a “4D” model of construction (1997). In addition to time, the 4D model includes “Responsive Workbench,” which is a state-of-the-art interactive graphics system that projects stereoscopic images onto a tabletop into a 3D model. Accounting for the actual spatial relationships at a discrete points in time may require several simplifying assumptions, as the number of components can be very large.

In addition to the spatial constraints imposed as construction materials are put in place, Tommelein (1998) considers the impacts of site logistics on the construction process. The research assigns a probabilistic function to the timeliness and location of resources that can significantly affect the construction process. For example, if all of the required steel beams are not on site at the time of erection, the entire process flow is hampered. Or, if the pipe sections for a plumbing system arrive too early on a congested site, they can impede the progress of the other systems.

In contrast to queuing models, graphic-based models can account for design specifics, and the design attributes can change throughout the process of construction. However, the graphic-based models still assume that the construction process itself remains fixed throughout the project. Processes and resources do not react to the change in system attributes as the building evolves.

Graphic-based models attempt to identify spatial constraints, but current research has only focused on large systems like steel erection and earthwork. Graphic-based plumbing models have yet to be modeled graphically. Among the graphic-based models that have been developed for



construction simulation, Vanegas and Opdenbosch (1994) have developed CADA (Computer-Aided Design and Assembly) to model the construction of a steel frame. Their model helps designers and builders to visualize construction operations in a “virtual environment” while a project is still in the early design phases. Stouffs et al. (1993) developed a program called RUBICON to model the construction of a precast concrete residential building. The model included the virtual simulation of two resources – a robot crane and a robot towmotor for handling palletized materials. With the RUBICON model, users specify the motional capabilities of the robots in an input file. An additional input file describes the characteristics and erection sequences of the concrete members. Using this information, the model produces a graphical representation of the construction process with respect to the operations of each robot.

### **2.2.3 Dynamic Process Models**

Dynamic process models represent a new approach to construction simulation. Similar to queuing models, dynamic process models simulate processes by following the flow of entities through a series of activities. However, in queuing models, the entities reflect resources. In contrast, the entities reflect the physical components of the building in dynamic process models. In other words, entities are the construction materials themselves, and they flow through a series of activities until the work on them is complete.

Entities can represent any size or component of a particular construction material. In the simulation of plumbing for example, entities can represent a run of pipe, or a pipe section, or a linear foot of pipe. Using a small entity size allows the model to simulate the process at the specific task level. This allows the user to control the level of detail that the model simulates. By simulating installation at a high level of detail, the models are able to capture the flexibility of the plumbing and fire protection processes more accurately.

As entities flow through the model, their attributes change as work is performed on them. The dynamic nature of the entities’ attributes allows for more flexible and accurate modeling of the overall process, because processing times and alternatives often depend on these attributes (Glasscock and Hale, 1994).

Glasscock and Hale originally developed dynamic process models for the chemical processing industry (1994) to predict the compositions of the various byproducts that are generated as chemicals are changed in a process. In chemical processes, the resources (mixers, tanks, etc.) remain fixed and cannot be re-allocated once processing begins. In construction though, resources are more flexible. They can move easily from one task to another, and so the order in which the resources perform tasks can significantly affect the rate of progress. When a change is made to the original process through

either a design change or innovation, resources may be reassigned to accommodate the change. Dynamic process models developed for construction can measure the secondary and tertiary effects of these reassignment opportunities.

Dynamic process models also handle the resource allocation process in construction differently than other models. Both dynamic process and queuing models use a resource “pool” to allocate resources, but the models assign the resources at different levels. Resources wait in a pool, and are allocated to processes or tasks as needed. In queuing models, resources are assigned at the process level, and move from one processing station to the next. Because the resources are allocated at this level, they have no flexibility to shift inside of a process. Dynamic models allow much more flexibility in terms of resource assignments, because the models assign resources at the specific task level. Many times, tasks differ within a process in terms of their resource requirements. For example, in the horizontal piping installation process, a ladder may be needed if the piping is above ten feet. However, the ladder is not needed for every task in the installation process. The tasks associated with cutting the pipe sections do not require a ladder. In the queuing model though, the ladder would be assigned to every task, including pipe cutting. The resource pool exists independently from the processes, which reflects the plumbing and fire protection trades’ approach to resource allocation.

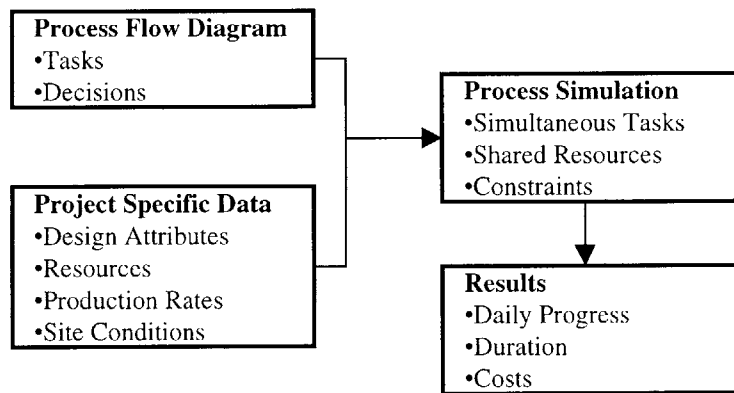
The idea of a “resource pool” accurately reflects the plumbing and fire protection trades’ approach to resource allocation. Any plumber or pipefitter can perform the majority of installation tasks, but the tasks must be sequenced around the installation of other building systems. As a result, foremen draw from their “pool” of plumbers as installation opportunities arise.

### **2.3 Dynamic Simulation Model for Plumbing and Piping Installation**

The dynamic process model serves as the basis for this simulation of plumbing and fire protection installation. The basic approach for the model is to examine the installation process from the smallest appropriate unit. This technique allows exploration and comparison of alternatives in design, components, materials, means, and methods at the smallest unit, where the associated activities are most accurately portrayed (Slaughter, 1997).

Dividing the simulation model into three inter-linked information components can simulate the complex interaction among the installation activities (Figure 2.1). The first component, a process flow diagram, breaks the installation process down into its detailed activities and tasks. The process flow diagram captures the logical sequences of necessary activities at the unit level, and then progresses hierarchically to capture the process flow at the building system level. The second model

component responds to changes in each project by organizing the project specific data that relates to each task determined in the process flow diagram. Project specific elements include system design attributes, type and quantity of installation resources, site conditions, and resource production rates. The process flow diagram and project specific data are then used to simulate the dynamic aspects of the installation process. Project dynamics simulate the real-world logical, technical, regulatory, and resource constraints that affect the installation process. For example, plumbing contractors may prefer to install vertical piping before horizontal piping, but the overall progress of the building may not allow plumbers to install vertical piping first. Upper floors may not be poured yet, so plumbers may have to install horizontal piping on the lower floors before installing vertical piping on the upper floors. Such constraints obviously effect the sequencing of the activities identified in the process flow diagram. These constraints are captured in the project dynamics component of the models.



**Figure 2.1: Components of the Installation Process Simulation Model (Slaughter, 1998)**

Dynamic process modeling is a fairly new approach to simulating construction activities. Previous models have been developed to simulate structural steel erection (Eraso, 1995), exterior enclosure installation (Attai, 1997), and cast-in-place concrete construction (Carr, 1998). Professor Sarah Slaughter at the Massachusetts Institute of Technology is currently developing a “meta-model” that will incorporate the previous building system models, the models developed here, and future models of electrical and HVAC systems into one model. This meta-model will simulate all of the construction-related activities required for the construction of a building.



### **3 Research Methodology**

The purpose of the dynamic process model for plumbing and fire protection is to assess the impacts of design changes and innovations on the installation process. To meet this objective, a research methodology was established to ensure that the model was valid, reliable, accurate, and representative. The research required collection and analysis of process flows, production rates, resource allocations, and costs. The simulation model was then incorporated into a computer simulation, and the model was tested on a plumbing and fire protection system for a prototype building. The validity of the results was confirmed through interviews with industry. Finally, the model was used to assess the impacts of six innovations.

#### **3.1 Process Identification and Model Development**

The process model for plumbing and fire protection installation was developed from three principle sources: existing literature, site observations, and interviews with industry. Literature provided general descriptions about installation process flows. Site observations and interviews helped to confirm the applicability of the literature to the “real-world,” and they also provided empirical data on production rates and dynamic constraints.

##### **3.1.1 Literature Review**

Literature used for the research included mechanical design and installation books, trade journals, articles, and “do-it-yourself” videos. Information gathered from the references served as a foundation for the preliminary process model (see Chapter 4) as well as for the design of the plumbing and fire protection systems for the prototype building (see Chapter 5). Trade journals also helped to identify resource requirements and production rates. Table 3.1 lists the references used to develop the preliminary process model.

Reference	Authors	Summary
Plumbing Systems (1997)	Wentz, T.	Analysis, Design and Construction
Mechanical and Electrical Systems in Buildings (1997)	Tao, W. Janis, R.	Plumbing and Fire Protection Design
Building Engineering and Systems Design (1997)	Merritt, F. Ambrose, J.	Systems Design
Plumbing Design and Installation Reference Guide (1986)	Hicks, T.	Design and Installation
Automatic Sprinkler Systems Handbook (1989)	National Fire Protect. Agency	Design and Installation
Professional Plumbing Techniques - Illustrated and Simplified (9184)	Smith, A.	Installation Tips for Plumbing and Fire
Plumbers and Pipefitters Library Volumes I, II, and III (1990)	McConnel, C.	Installation Guidelines for Plumbing
Uniform Plumbing Code (1997)	Int. Assoc. of Plumb. Officials	Design and Installation Codes

**Table 3.1 References Used for Model Development**

### 3.1.2 Site Observations

During the process identification phase, site visits were used to confirm and improve upon the validity of the preliminary process model. Many of the tasks required in plumbing installation are experiential, and consequently cannot be found in technical references. Direct observation through site visits was necessary to identify these steps for the development of the model. For example, plumbers usually install the hangers for a horizontal pipe run before connecting the pipes. However, none of the technical references listed in Table 3.1 discuss that technique.

Data on production rates and activity processing times is available in references like R.S. Means Mechanical Cost Data (1997). However, the data is arranged for use with the Quantity Take-Off method described in Chapter 2. In order to apply the necessary data to the dynamic process model, empirical data on installation activities was gathered from site visits. Processing times and resource requirements for activities were determined through on-site observation.

Numerous construction sites were visited in the Boston area to obtain a larger database of information. Particularly useful sites were visited several times to identify techniques and constraints throughout the installation process. Table 3.2 lists some of the more helpful construction sites visited.

Project Name	Location	Comments
Doubletree Hotel University Park	Cambridge, MA	8-Story hotel with a supermarket on the first two floors.
75 Sidney Street	Cambridge, MA	5-story biotech research facility. Plumbing plan requires special runs for numerous chemicals.
Logan Airport Hotel	Boston, MA	10-story hotel. Penthouse Mechanical Room.
Harvard Business School	Cambridge, MA	8-story Extended-Stay hotel. Water Heaters zoned on each floor.
Two Canal Park Galleria Office Building	Cambridge, MA	5-story Office Building Bathrooms located in building core, mechanical rooms every other floor.
Cambridge Center Office Building Kendall Square	Cambridge, MA	9-story office building. Two sets of bathrooms on each floor, downfeed hot water supply.
Polaroid Building	Cambridge, MA	5-story renovation to an office building. Entire plumbing and fire protection system was replaced.
Mount Auburn Hospital	Cambridge, MA	Renovation of a hospital, including a replacement of the plumbing system.
Seaport Hotel (World Trade Ctr)	Boston, MA	18-story hotel, with mechanical rooms every 5 floors. Downfeed hot water supply system.
Stop & Shop (Ryerson Steel Site)	Brighton, MA	2-story retail facility with cafeteria. Standard fire protection system.
Marriot Residences Kendall Square	Cambridge, MA	14-story hotel. Fire protection uses PVC for distribution into rooms.
Pilot House (Lewis Wharf)	Boston, MA	Renovation of a 6-story office building. Two sets of bathrooms on each floor,
Aquarium	Boston, MA	Renovation of a 6-story aquarium. Complex plumbing system required.

**Table 3.2 List of Construction Sites Visited for Data Collection**

### **3.1.3 Interviews with Industry to Develop and Verify the Models**

Despite numerous site visits and technical references, accurate and reliable data on every activity associated with the installation process was not readily available. Interviews with members of the plumbing and fire protection industry were used to fill the voids in the information regarding process flow, project specifics, and project dynamics and to validate data collected through other sources. An interview with Joseph Valante, President of Valante Mechanical Corporation, for example, revealed the importance of installing drainage runs before supply runs for a bathroom because of the critical pitch requirements of drainage piping. The interviews also helped to explain

some of the variances found between construction theory and construction practice. Table 3.3 lists the Industry members interviewed for the development of the initial process model, as well as for verification of the completed model.

Industry Contact	Position	Company
Dick Howarth	Chief Estimator	Fishbach Corporation Englewood, CO
John Ziegenheim	Estimator	The Poole and Kent Comp. Baltimore, MD
Marty Sanderholm	Estimator	MMC Corporation Leawood, KS
Jack Howison	Project Manager	McKenneys, Inc. Atlanta, GA
Dave Inks	Estimator	Hunter Corporation Portage, IN
Pat Larson	Chief Estimator	Fullman Company Portland, OR
Dan Sackett	Estimator	Harris Mech. Contr. Comp. St. Paul, MN
Frank Sacchetti	Project Manager	Ivey Mechanical Company Koscinko, MS
James Claus	Estimator	Limbach Constructors Pittsburgh, PA
Tim Roberts	Estimator	Monterey Mechanical Co. Oakland, CA
Arthur D. Dowd	President	Dowd Plumbing Inc. Quincy, MA
Joseph Valante	President	Valante Mechanical, Inc. Boston, MA
Jim Craig	Estimator	R.G. Vanderweil Engineers Boston, MA
Duane Rainey	Estimator	TD Industries Dallas, TX

**Table 3.3 List of Industry Contacts**

#### **3.1.4 Verification of Model**

The preliminary process model was sent out to the members of the plumbing and fire protection industry listed in Table 3.3 for review. Fifteen senior estimators and project managers from around the country were sent a packet that contained the material listed in Table 3.4.



Item	Description
Process Flow Diagram	50 pages containing the flow charts shown in Appendix A.
List of Design Attributes	A summary of the critical design attributes that determine processing times and entity attributes.
Resource List	A list of resources used in installation, including typical crew sizes/ratios, large equipment, and individual tools used.
Summary of Production Rates	Summary of general installation activity durations. For example, fixture installation times, etc.

**Table 3.4 Summary of Packet Sent to Industry Members**

Industry input was solicited from different parts of the country to see how the process differed in different geographic regions. Follow-up interviews were then conducted with the industry members to confirm the representativeness of the model. As expected, responses varied slightly by geographic region and among companies. For example, plumbers in the South typically install water service meters themselves, whereas plumbing contractors in northern regions must allow the city water authority to install the meters. Also, approximately 70% of the contractors interviewed felt that prefabrication of bathroom systems saved a substantial amount of labor costs, whereas the other 30% of contractors felt that the labor savings were minimal. Comments derived from interviews were used to revise the original model to more accurately reflect industry practices from around the country.

### **3.1.5 Process Model Development**

The information gathered from literature, site observations, and interviews served as the basis for the development of the process model. In addition to the model, a list of associated activity durations and resource requirements was generated from the process identification phase.

## **3.2 Computer Simulation of the Process Model**

Once the process flows had been verified, development of the computer simulation model began. In order to test the validity of the computer model, project specifics were developed through the design of a prototype plumbing and fire protection system for a building. Innovative plumbing designs, materials, and methods were also identified and modeled for computer simulation testing.

### **3.2.1 Plumbing and Fire Protection System Design for the Prototype Building**

The project specifics for the model require detailed information about material type, quantity, and spatial arrangement for the plumbing and fire protection systems. To satisfy these requirements, a set of blueprints detailing the plumbing and fire protection systems for a prototype building were created.

The blueprints, shown in Chapter 5, were drawn on AutoCAD for ease of modification. The intent of the design was to represent a simple, yet realistic system that could test the processes identified in the model. The intent was not to design the most efficient or elegant system for a particular building type. Nevertheless, a mechanical design firm, R.G. Vanderweil Engineers, was consulted in the design of the prototype systems to ensure that the system was realistic and logical.

The design attributes of the prototype building were determined from the blueprints, and were then transferred to computer spreadsheets. The spreadsheets are used to feed information into the computer model program, as discussed in Chapter 5.

### **3.2.2 Identification of Innovations for Simulation**

The model's ability to assess innovations in design, materials, means, or methods was tested through the inclusion of recent plumbing innovations into the model. Plumbing and fire protection innovations were identified through a review of research documents and conferences, industry periodicals, and interviews with industry leaders. These sources provided details on the critical aspects of the innovations. Based on these descriptions, the modeling implications of the innovations were added to the process model, and each innovation was tested for its effects on the overall installation process. Chapter 6 describes the innovations in greater detail.

### **3.2.3 Computer Simulation**

SIMPROCESS, a commercially available process simulation program, was used as the platform for the computer model. SIMPROCESS contains a graphical-user-interface (GUI) to facilitate creation and management of a dynamic process model. The process model and corresponding resource descriptions were used as a basis for development of the computer model. Chapter 5 explains the computer model in greater detail.

### **3.3 Validation of Results**

The plumbing and fire protection simulation models are designed explicitly to respond to elements that change on each project. Specifically, the models respond to design attributes (materials, arrangement of materials) and resources (quantity and associated production rates).

The “human factor” will never be perfectly represented in a simulation model, so a degree of inaccuracy is to be expected in any simulation. Also, the sequence of plumbing installation tasks depends heavily on the rate of progress of surrounding building systems, including concrete placement, HVAC installation, and interior finish work. As a result, actual plumbing installation times and production rates vary greatly from project to project. However, the ability of the models to respond to design and resource specifics makes them flexible enough to simulate individual data on production rates. Therefore, the production rates used for the models presented here are simply approximations based on empirical data gathered from interviews and site observations. Users of the models can and should modify the production rates and processing times to reflect the individual user’s rates. As the model is used more often, its accuracy will improve, as more data becomes available.

The utility of the models, in terms of serving as reliable and representative simulations, is validated through comparison of the simulation results with actual projects and industry opinion.

#### **3.3.1 Prototype Model Validation**

Once the project specifics and process flows were incorporated into the computer model, the installation process was simulated. The simulation results, including overall installation times, resource efficiencies, and sequencing of work were then verified with industry members to gauge their accuracy. Comparisons were made with actual building installation projects similar to the prototype system, and were found to be within 10%. Industry members also validated the model’s accuracy through comparisons with their own estimating methods.

#### **3.3.2 Innovation Testing**

Having established the validity of the plumbing and fire protection process models, the models were then used to assess the impacts of the innovations on the installation process. Separate models were run for each innovation, and the simulation results were compared with the baseline model. Chapter 6 summarizes the results of the simulations run for each innovation.



## 4 Installation of Plumbing and Fire Protection Systems

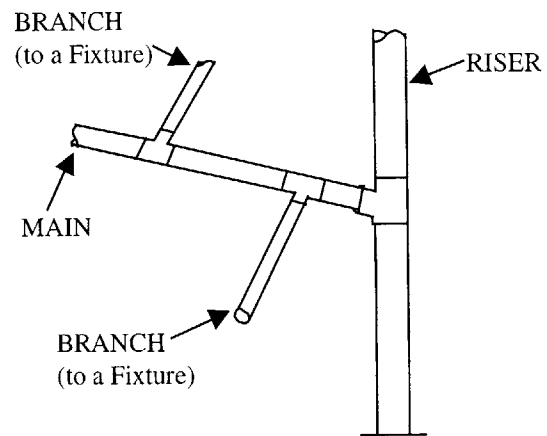
Development of an accurate dynamic process model requires a comprehensive understanding of the installation processes for plumbing and fire protection systems. Design aspects, as well as specific tasks associated with installation must be represented in the simulation. This section identifies the basic principles of plumbing and fire protection systems, and outlines the processes associated with their installation.

### 4.1 General Description of Plumbing and Fire Protection Systems

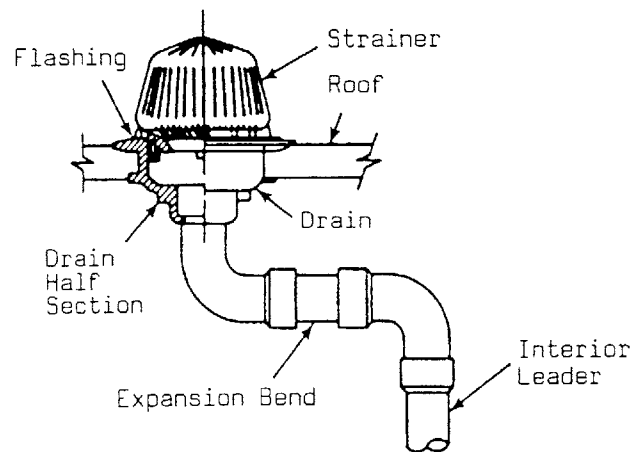
In order to understand the installation process, a general understanding of the systems themselves is necessary. The focus of this section is to describe how and why plumbing and fire protection systems work, and how they relate to the other systems in a building. Key terms and definitions that are used in the model are listed in Table 4.1 below. Figures 4.1 through 4.5 clarify the terms listed in the Table.

Term	Definition
Branch	Piping that comes off of a main to feed into a fixture.
Building Drain	The lowest piping of a drainage system. It receives the discharge from drainage pipes inside the building and conveys it to the public sewer system outside the building.
Main	The principle pipe artery which feeds off a riser and connects to branches.
Riser	A water supply pipe that extends vertically one full story or more to convey water to branches or fixtures.
Roof Drain	A drain installed to receive water that collects on the surface of a roof.
Rough In	The installation of all parts of the plumbing system that can be completed prior to the installation of fixtures.
Stack	A drainage or vent pipe that extends vertically one full story or more to convey waste from fixtures or drains.
Sprinkler Heads	Heat-sensitive outlets for fire protection piping. Spaced at specified intervals, they release water when they reach a predetermined temperature.
Standpipe	A vertical pipe in which water is stored under pressure or which can be rapidly supplied with water. Used for fire protection, it has outlet valves on each floor for connection to fire hoses.
Support	A device used to support and stabilize pipes, fixtures, or equipment. Includes hangers and clamps.
Trap	A fitting that provides a liquid seal to prevent the emission of sewer gases through fixtures.
Vent	A pipe installed to provide circulation of air to and from the drainage system. Can be vertical (stack) or horizontal (branch).
Water Service Pipe	The pipe that extends from the public water supply main to the water distribution system for a building.

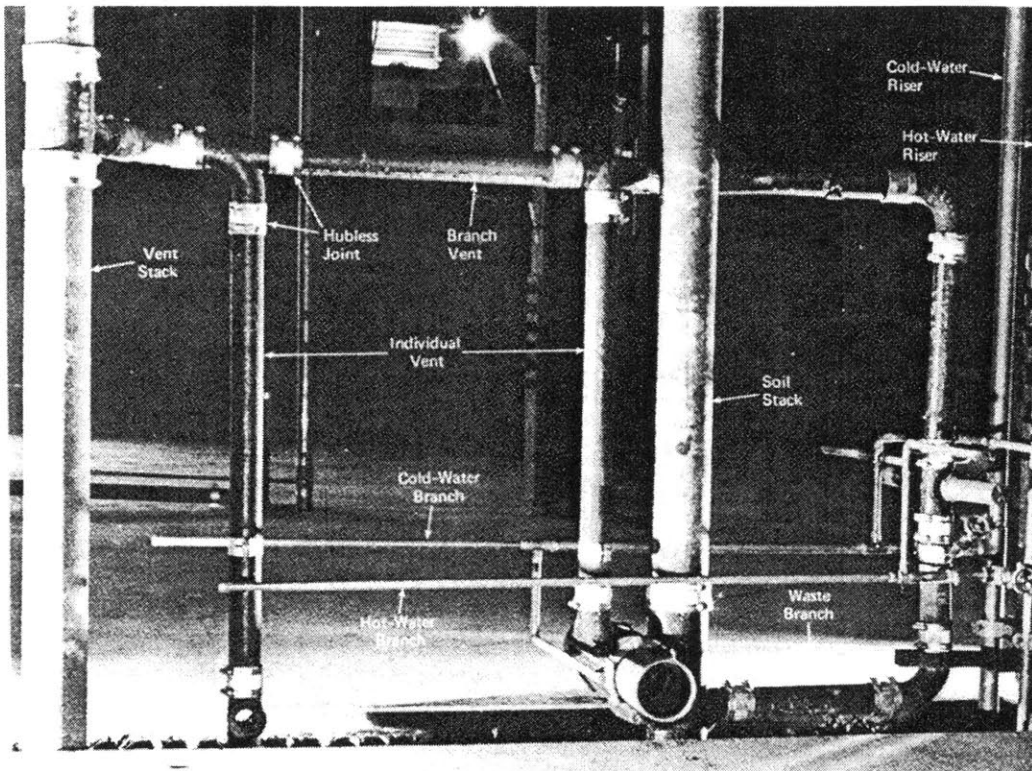
**Table 4.1 – Plumbing and Fire Protection Terms**



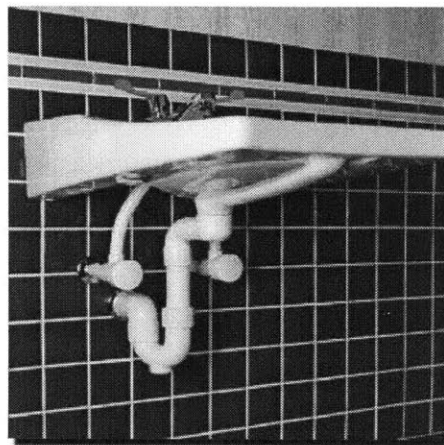
**Figure 4.1: Relationship between Risers, Mains, and Branches**



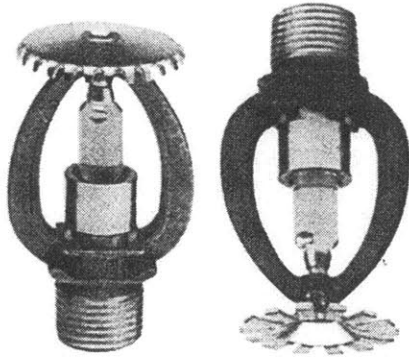
**Figure 4.2: Roof Drain Schematic (Merrit & Ambrose, 1990)**



**Figure 4.3: Rough-In for a Bathroom System (Merrit & Ambrose, 1990)**



**Figure 4.4: Trap Seal for A Lavatory (Sink) (TrueBro®, 1998)**



**Figure 4.5: Sprinkler Heads for Fire Protection (Tao & Janis, 1997)**

#### **4.1.1 Plumbing Systems**

The basic intent of a plumbing system is “to create a healthy environment that provides an adequate amount of potable water, and a safe, healthy method of collecting and disposing of liquid and solid wastes” (Wentz, 1997). Safe and potable water is provided through domestic water supply methods, and wastes are collected and disposed of through wastewater removal systems.

##### **4.1.1.1 Domestic Water Supply**

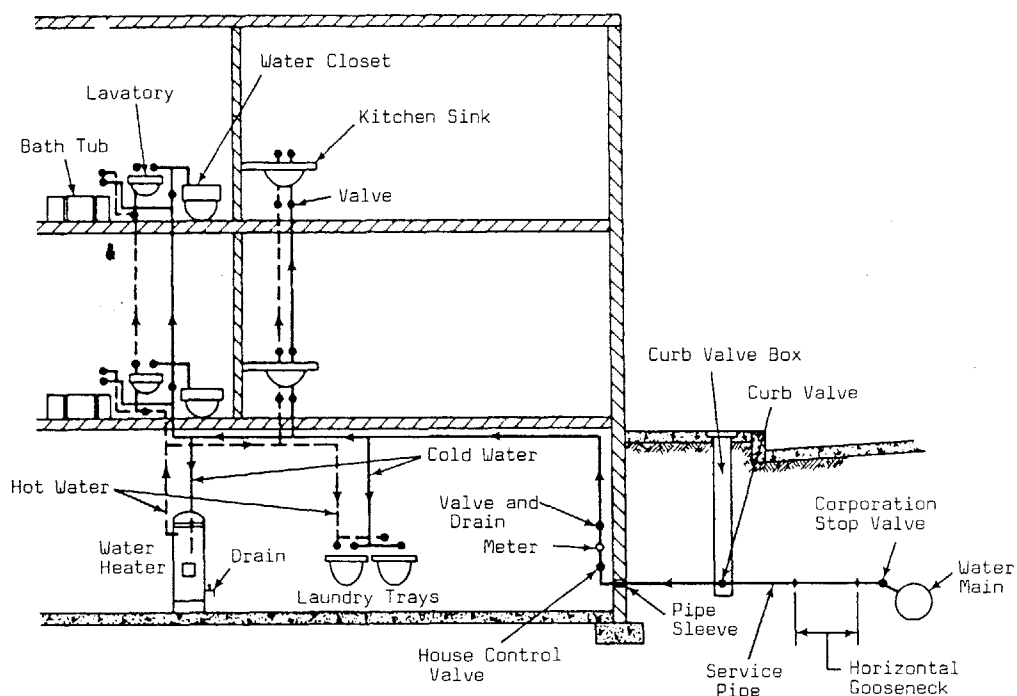
Domestic water distribution systems must provide water to all plumbing fixtures at an adequate pressure and temperature. Water is distributed through a system of pipes, and flows from points of higher pressure to points of lower pressure until it is expended through a fixture. The pressure differential is caused by either the higher pressure of the incoming water, gravity, externally applied pressure (pumps), or temperature differential. Water loses pressure as it flows through the pipes as a result of friction caused by the surface of the pipes, fittings and valves. The plumbing system design must account for this pressure loss to ensure adequate pressure at the fixtures. Pressure ratings vary for different fixture requirements, but are typically between 8 and 25 pounds per square inch (56 and 175 kilo-Newtons per square meter).

Domestic water is supplied through a water service pipe that extends from a public water supply system into the building. Water then passes through any necessary meters and equipment, and is split into hot and cold water risers that extend vertically up the building. Mains feed off of the risers at each floor, and branch off to serve fixtures. In commercial buildings, the piping system for a particular floor



is usually located above the ceiling tiles, and branches downward into the fixtures. In residential or industrial buildings, however, the piping system may be located below the floor slab for each floor, or may be imbedded in interior and exterior wall studs.

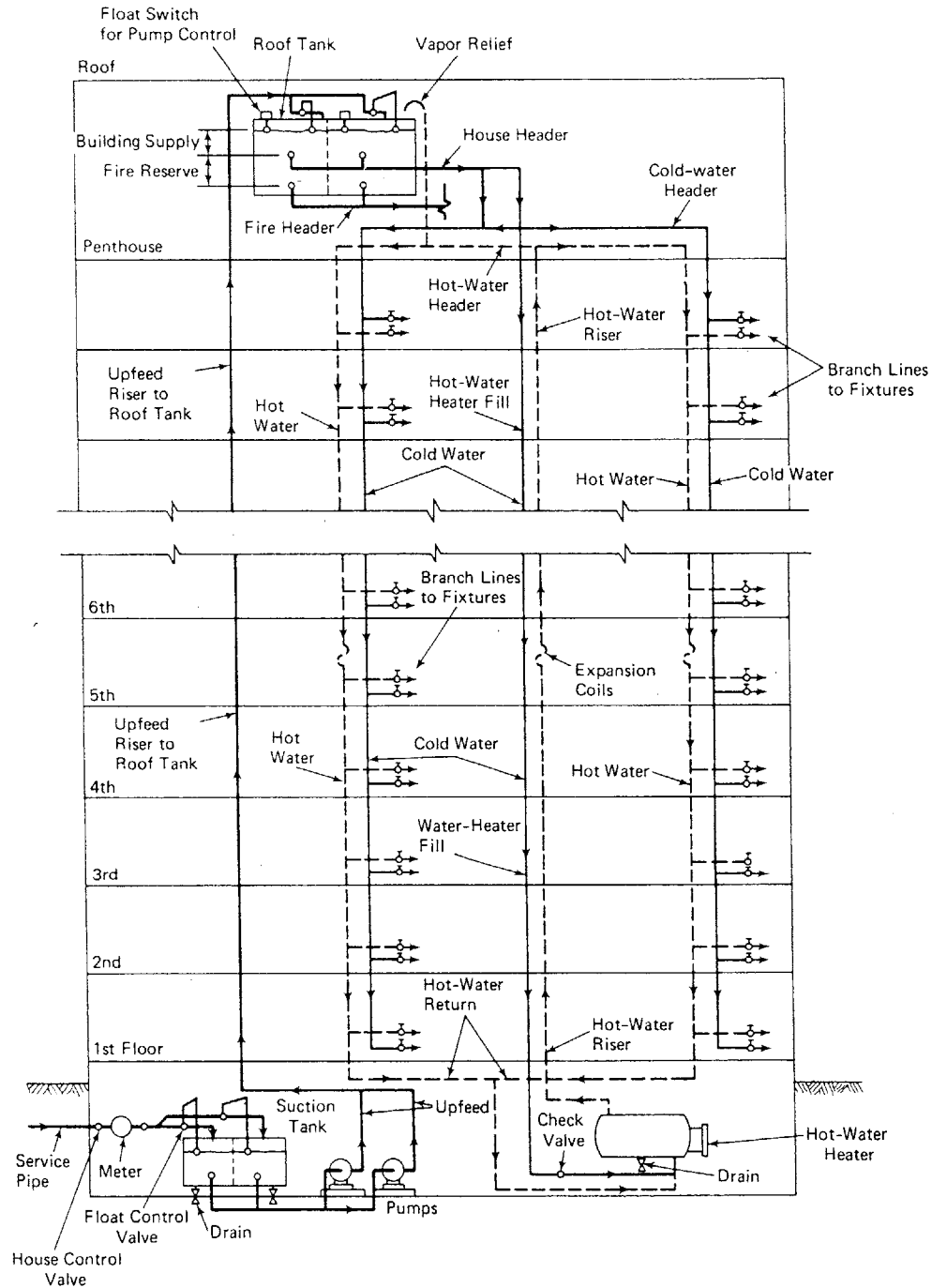
Domestic water can be conveyed to fixtures through either an upfeed or downfeed distribution system (Merritt & Ambrose, 1997). In the upfeed system, risers carry water upward under the pressure supplied by the water service pipe. Since the risers rely on the pressure of the external water source, upfeed systems are only suitable for buildings that are less than six stories (Merritt & Ambrose, 1990). Figure 4.6 illustrates an upfeed water distribution system.



**Figure 4.6: Upfeed Water Distribution System (Merritt & Ambrose, 1990)**

For buildings taller than six stories, a pump is necessary to supply adequate pressure at the higher-level fixtures. This is typically accomplished through a downfeed system, where incoming water is pumped to an elevated storage tank, from which pipes convey the water downward to fixtures and water heaters. The water heaters usually remain at the bottom of the system. Hot water from the heaters rises to a hot water header in the penthouse through a temperature differential. The header then distributes the water to downfeed risers that branch out to the fixtures, and unused hot water is

recirculated to the water heaters. Very tall buildings are often divided into zones, each with its own downfeed system. Figure 4.7 illustrates a downfeed water distribution system.



**Figure 4.7: Downfeed Water Distribution System (Merrit & Ambrose, 1990)**

#### 4.1.1.2 Wastewater Removal Systems

The drain, waste, and vent system (DWV) collects the discharge of the various fixtures, as well as rainwater or other liquid wastes, and conveys it to a legal disposal point (usually a city sewer main). Unlike the supply system, the DWV system is self-reliant, using gravity as its principal source of conveyance.

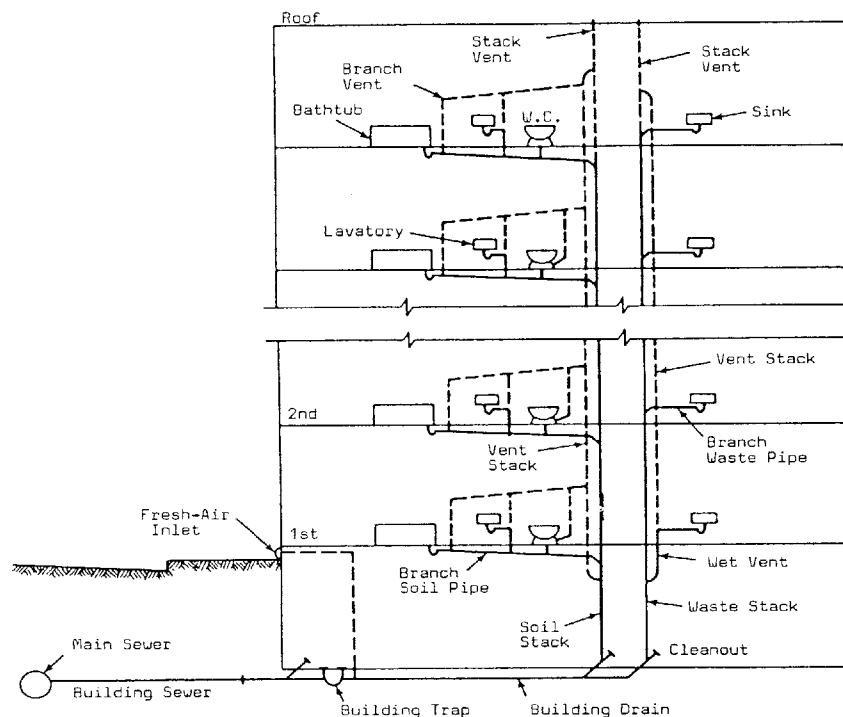
Wastewater is first collected through drains. Drains are located in fixtures, in floors (floor drains), or on roofs (roof drains). In accordance with the National Standard Plumbing Code (1997), “each plumbing fixture directly connected to the drainage system shall be equipped with a liquid seal trap.” The trap prevents harmful gases from the DWV system from seeping through the fixture.

Waste is conveyed via gravity through sloped horizontal branch pipes. The branch pipes are usually sloped at  $\frac{1}{4}$  inch per foot (2 centimeters per meter), and move the waste to vertical stacks. Horizontal branch pipes for a particular floor are usually located just below the floor slab. Stacks feed the waste to the building drain, which must be below the level of all other drains. The building drain conducts the water to the city sewer system located outside the building.

Vents supply the drainage system with a continuous flow of air from outdoors to help minimize the back siphonage and the buildup of harmful gases. Fixtures are either connected directly to a vent stack, or else to a branch vent. Branch vents serve several fixtures, and connect to a vent stack. Unlike drainage systems, however, vents slope upward towards the vent stack, usually at a pitch of  $\frac{1}{4}$  inches per foot (2 cm/m). Vent stacks extend through the roof to expel harmful odors and to collect fresh outdoor air.

The pitch requirement can severely affect floor-to-ceiling heights for long horizontal drainage runs. For example, a 20-foot run (6.5 meters) affects the ceiling clearance by eight inches (22 cm). To counter this problem, mechanical designers try to minimize horizontal DWV runs by installing DWV stacks as close to fixtures as possible, even if additional stacks are necessary.

Roof drainage systems are similar to the DWV systems for fixtures, but usually feed into a separate city storm sewer line. For this reason, roof drainage lines are not tied into the DWV system that serves the fixtures and floor drains. The drains that feed into roof drainage systems are usually covered with grates to prevent clogging. Figure 4.3 illustrates a wastewater removal system for a building.



**Figure 4.8: A Wastewater Removal System for a Building (Merrit & Ambrose, 1990)**

#### 4.1.1.3 Pipe Materials

Numerous different pipe materials are used in plumbing systems. Several factors go into the choice for the optimum pipe material. Table 4.2 below highlights the criteria used for selection.

Criteria	Explanation
<b>Response to Corrosion</b>	Pipe must withstand the corrosiveness of the fluid being conveyed, especially for acid waste conveyance.
<b>Temperature</b>	Hot-water pipes must be able to withstand high temperatures. Outside temperatures affect the pipe's performance as well.
<b>Pressure</b>	For highly pressurized systems, (like some fire protection systems), the pipes and fittings must have adequate strength.
<b>Regulations</b>	Local codes vary on what materials are permitted for different uses.
<b>Cost</b>	Pipe materials vary greatly on both material and installation costs.
<b>Aesthetics</b>	Some designers may choose a material for its noise performance or appearance.

**Table 4.2: Selection Criteria for Pipe Materials (Wentz, 1998)**

Based on the criteria listed above, Table 4.3 below summarizes the common uses for various pipe materials. Pipe materials differ from each other in several ways, including strength, weight, wall thickness, connection type, section length, chemical characteristics, and resistance to corrosion.

Pipe Material	Principle Uses
Copper	Domestic Water Supply, Gas, Some Sanitary Plumbing
Plastic (ABS, PVC)	Sanitary Piping in Some locations
Cast Iron	Drain, Waste, and Vent Piping (DWV)
Steel	Fire Protection, Some Vent Piping

**Table 4.3: Common Pipe Materials and Their Use (Wentz, 1998)**

#### 4.1.1.4 Equipment

In addition to pipe materials, various types of equipment are often used to power and regulate the system. Table 4.4 below lists some of the major equipment pieces used in building plumbing systems.

Equipment	Description
<b>Backflow Preventer</b>	A device installed directly into a water distribution line to prevent backflow.
<b>Pressure Reducing Valve</b>	A valve used to reduce the pressure in a piping system.
<b>Pump</b>	A device used to increase the pressure in a piping system. Usually used to convey water to upper floors.
<b>Water Heater</b>	A device used to increase the temperature of the water in a distribution system. Usually is an electric or gas powered tank in a range of sizes.
<b>Water Softener</b>	A device used to reduce the hardness (increase the pH) of incoming water.
<b>Service Meter</b>	A device installed near the service pipe to measure usage. Usually installed by city officials.

**Table 4.4: Major Equipment Types for a Building (Merrit & Ambrose, 1990)**

#### 4.1.1.5 Fixtures

Fixtures act as the interface between users and the plumbing system, and are divided into six categories: water closets (commonly referred to as toilets), urinals, sinks, showers/bathtubs, drains, and drinking fountains. For each category, thousands of variations exist to meet local technical and aesthetic needs. The plumber must address the design and installation impacts of these variations.

Water closets and urinals only require cold water supply. Sinks and showers usually require both hot and cold water lines and drinking fountains often use a separate chilled water line.

#### 4.1.2 Fire Protection Systems

The principal intent of a fire protection system is: 1) to detect a fire or smoke, 2) to actuate a signal, and 3) to suppress the fire or smoke in order to protect lives and save property (Tao & Janis, 1997). This simulation focuses on the installation of fire protection piping, so the detection and signaling systems employed in fire protection will be ignored. Instead, the following sections will focus on the suppression systems, namely fire sprinklers and standpipes.

Fire suppression systems consist of a combination of standpipes and automatic sprinkler systems that are employed to suppress a fire. They are usually supplied with water from a source separate from the plumbing distribution system, or from the fire reserve of an elevated tank. Figure 4.9 illustrates a typical fire protection system.

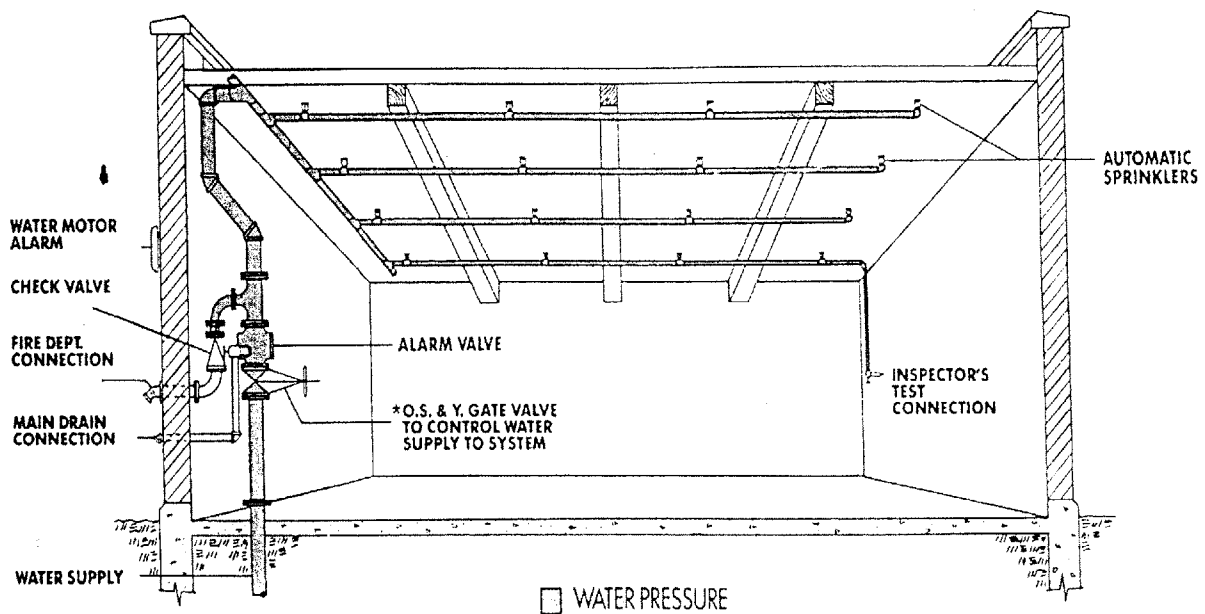


Figure 4.9: A Fire Protection System (Tao & Janis, 1997)

A standpipe is a vertical pipe in which water is stored under pressure or which can be rapidly supplied with water. Standpipes are equipped with riser outlet valves at each floor for quick connection

to fire fighting hoses. Standpipes are usually located within stairwells to allow easier access for the hoses.

In addition to the standpipes, sprinkler systems are used to suppress the fire automatically through nozzles located at intervals on each floor of a building. As Figure 4.4 shows, sprinkler systems are similar to upfeed or downfeed systems for plumbing. They originate at a fire pump or from a storage tank, and water is transported to higher floors via risers. A network of horizontal mains and branches stem off of the risers at each floor, and feed into sprinkler heads that release the water during a fire.

Horizontal piping for fire protection systems does not have to be sloped as steeply as for plumbing (some regulations may specify a 1/8 inch per foot (1 cm per m) slope towards the risers), so minimization of horizontal runs is not a large constraint in fire protection systems. In fact, fire protection systems seek to maximize coverage with the minimum number of vertical penetrations (Craig, 1998). As a result, fire protection systems usually consist of a horizontal grid of pipes located above the ceiling tiles for a floor.

Sprinkler heads are placed at appropriate intervals to reach all areas of a floor in case of fire. The heads are heat sensitive, and will discharge water when the temperature at the head reaches a predetermined level. The sprinkler intervals depend on local codes and building types. Table 4.5 lists the National Fire Protection Agency's recommended spacing intervals for various building types.

<b>Hazard Level</b>	<b>Maximum Protection Area, Square feet (S.F.)</b>
<b>Light</b> warehouses, storage	Concrete and steel frame - 200 S.F. Open Wood Joist - 130 S.F.
<b>Ordinary</b> offices, residential, hospitals	130 S.F., must have at least 1 sprinkler per room, without any sprinkler obstructions
<b>Extra</b> industrial, chemical, labs	100 S.F., must have at least 1 sprinkler per room, without any sprinkler obstructions

**Table 4.5: NFPA Sprinkler Head Interval Requirements (Allen, 1997)**

Fire protection systems are classified as either wet-pipe or dry-pipe systems. In wet-pipe systems, the pipes always contain water, but the water doesn't actually flow until a sprinkler head opens. Wet-systems must always be maintained at a temperature above freezing.

Dry-pipe systems do not contain any water until a sprinkler head is open, so they can be used in buildings where temperatures drop below freezing. In a dry-pipe system, the pipes are pressurized to keep water from entering the system. When a sprinkler head opens, the pressure in the system is released, and water flows to the sprinkler head.

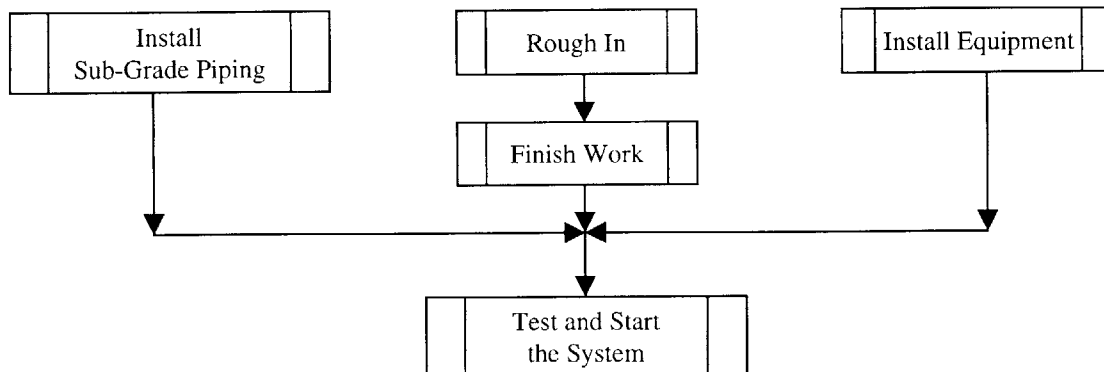
As in plumbing, there are several different piping materials available for fire protection systems. Regulatory codes are strict though, and in most places, sprinkler pipes must be made of wrought steel (NFPA 13, 1997).

## 4.2 General Description of Plumbing and Fire Protection Installation

The general processes associated with installation are the same for both plumbing and fire protection systems. In fact, contractors often will install both systems for a building. For this reason, the general process described below refers to either system.

### 4.2.1 Overall Process Description

Installation can be broken down into five major sub-processes: 1) Installation of Sub-Grade Piping, 2) Rough-In of the System, 3) Finish Work, 4) Installation of Equipment, and 5) Test and Startup. Figure 4.5 summarizes the relationship between the major tasks.



**Figure 4.10: General Process Flow**

As Figure 4.10 illustrates, the sequence of the major installation activities is rather flexible for a building as a whole. The only true precedence relationship exists between rough-in and finish work, because the rough-in must be tested before a fixture can be installed. In reality though, plumbers are



limited in their resources, and are constrained by the progress of the other building systems. These constraints lead to a process flow that is dictated by priorities and availability rather than predecessor-successor logic.

Installation of sub-grade piping usually begins shortly after the building foundation has been completed. Sub-grade installation must be complete before the concrete slab-on-grade is poured.

As the building progresses upward, plumbers begin the process of rough-in. This process includes the installation of sleeves, hangers, and all piping extending out to connect with fixtures, or in the case of fire protection, extending out to the sprinkler heads. The rough-in process is typically the most time consuming, and moves at the pace of the building as a whole.

Installation of equipment can take place at virtually any point in the progression of the building. Once a mechanical room has been designated and a floor poured, plumbers can move in the necessary equipment.

Finish work includes the installation of fixtures for plumbing systems, and the installation of sprinkler heads for fire protection. Finish work cannot begin however, until the rough-in is completed and tested. It is also constrained by the progress of interior finishing as a whole, because fixtures cannot be installed until interior walls are finished.

Plumbers usually work from the bottom floor up during the rough-in phase of installation. For finish work, they typically follow the interior finish crews, and progress from the top floor down. Following installation of the fixtures and sprinkler heads, the building system is “turned on” by filling and pressurizing the pipes in the system. Equipment begins to regulate the system, and a final test of each fixture is made before turnover.

#### **4.2.2 Repeating Sub-Processes in Piping Installation**

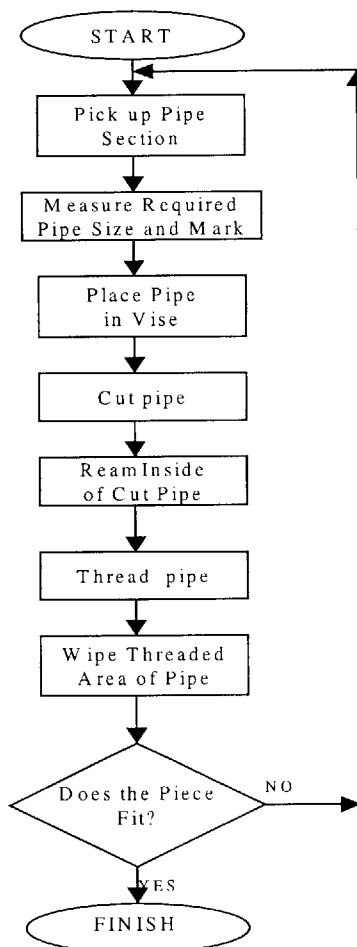
Plumbing and Fire Protection systems consist largely of piping, as piping is needed to transport the liquid or waste to and from various points in the building. Consequently, installation of the systems involves a significant amount of pipe installation.

The process of pipe installation is very repetitive in its nature. It consists of three basic steps: prepare, connect, and support. These sub-processes are used extensively throughout the plumbing and fire protection installation processes. The tasks within the sub-processes remain the same throughout installation, but the order of the three sub-processes can change based on the activity being performed. In horizontal pipe installation, for example, a pipe section is first prepared for connection. Hangers may be installed simultaneously by another crew. Once, the pipes are ready, they may be lifted into place. The pipe sections are then connected through the hangers, and the hangers are adjusted to support the

pipes at the right height. In vertical pipe installation though, pipes are connected before they are supported by clamps to the floor slab.

### ***Pipe Preparation***

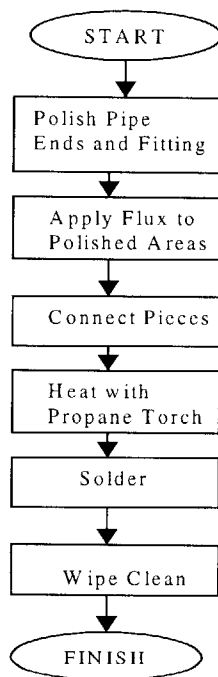
Figure 4.11 illustrates the basic steps involved in the preparation of a pipe run. First, a journeyman or foreman plots and measures where the pipe run will go. Once the pipe run has been measured, the required number of pipe sections and fittings is gathered, and any necessary cutting or threading is performed on the sections. Usually, a journeyman or apprentice cuts the pipe sections using either a hand-held or table sized pipe cutter.



**Figure 4.11: The Preparation Process**

### ***Pipe Connection***

Following preparation, pipe sections must be connected to form a continuous run of pipe. Usually one person can physically connect two pipe ends, but an additional person may be necessary to hold the ends in place during connection. The type of connection used varies, depending on the type of pipe and the pipe's purpose. Connections can be mechanical (bolted, threaded, rolled), chemical (adhesive connections), welded (soldered, arc-welded), or compression (compression, gaskets). The two sections being connected are usually held together by a fitting. Fittings include elbows, tees, and couples. Appendix A describes various processes for different types of pipe connections. One of these types of connection processes, soldered pipe connection, is illustrated in Figure 4.12 below.

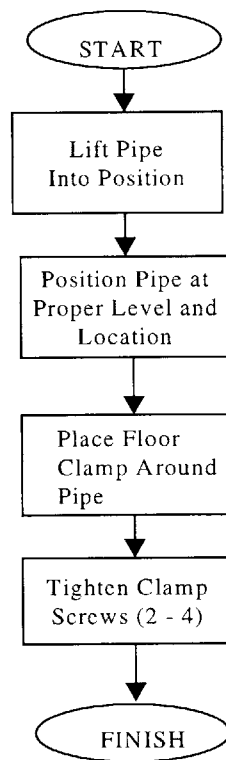


**Figure 4.12: The Connection Process for a Soldered Connection**

### ***Pipe Support***

Piping systems must be physically supported by the building to prevent displacement and damage. Supports include clamps for stacks and risers, and hangers for horizontal runs. Usually, a team of two people is required to install supports. In the installation of hangers for example, one person physically attaches the hanger to the building, while another person cuts and prepares the hangers to be installed. In this case, the pipes are inserted into the hangers after the hangers are in place. In vertical piping, however, the pipe is first lifted into position, and then a second person attaches a floor clamp

around the pipe's base to support the pipe. Figure 4.13 outlines the general steps involved in supporting a vertical section of pipe.



**Figure 4.13: Installation of Supports for a Vertical Pipe**

The repetitive processes listed above can be captured quite accurately in the simulation model. Appendix A contains the complete set of flow diagrams for the installation of various pipe materials.

#### **4.2.3 Progress with Respect to Overall Building Progress**

As mentioned earlier, the installation process for plumbing and fire protection systems depends heavily on the progress of the building system as a whole, because most plumbing tasks require that other building systems already be in place. For example, once the rough-in for a bathroom has been completed and tested, the next task in the process is to install the fixtures. Fixture installation must wait for the interior walls to be installed first, though, and this interior wall erection process is independent from the plumbing installation process. To accurately account for this exterior disruption, a complete

model, which can account for all of the building systems and their interdependencies, is necessary. As mentioned earlier (see Chapter 2), this “meta-model” is currently under development, and will include the plumbing and fire protection models developed here. The inter-relationships among the various building systems will be addressed by the meta-model, and are therefore beyond the scope of this research paper.

## **4.3 Specific Processes**

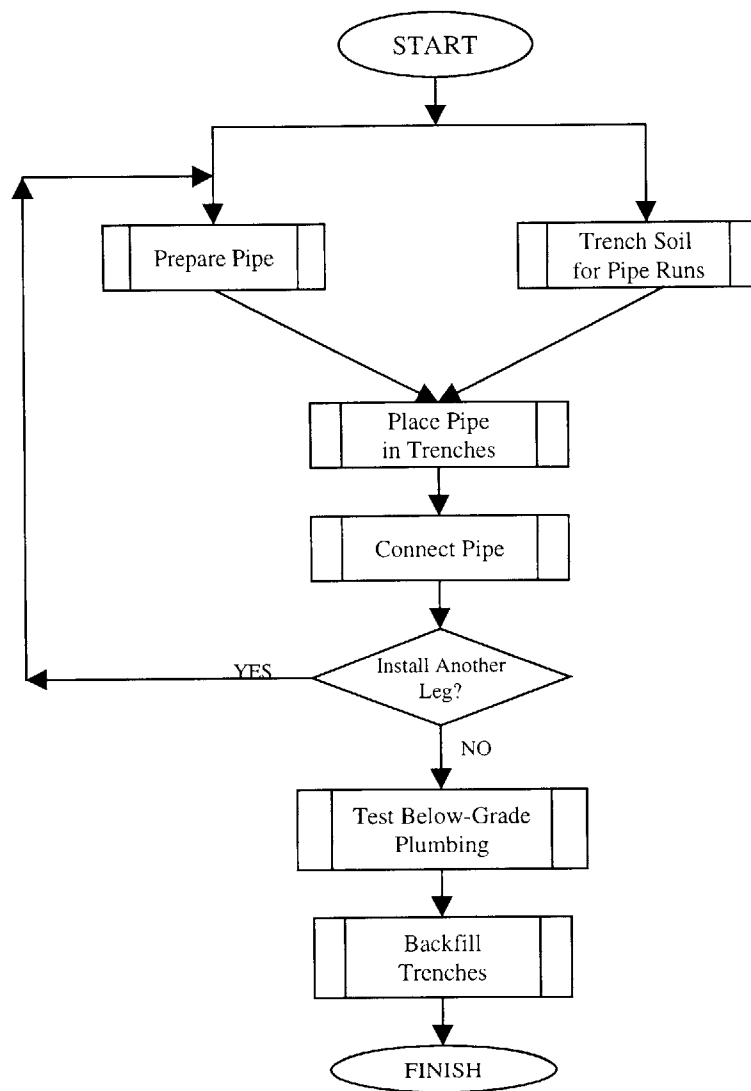
The detailed nature of the dynamic process model requires a deeper understanding of the general processes involved in the plumbing and fire protection installation. This section describes each of the major installation sub-processes (see Figure 4.10) in greater detail. The major installation sub-processes will refer often to the Prepare, Connect, and Support processes that were described in Section 4.2.2.

### **4.3.1 Installation of Sub-Grade Piping**

Sub-Grade piping includes any piping that is installed underneath the building. It does not include piping that is installed in basements, because basement-piping systems are similar to the systems found on any other floor. Sub-grade plumbing, however, is installed directly into the ground and requires trenching.

The installation process for sub-grade piping is outlined in Figure 4.14. First, a trench must be dug for the piping runs, usually using a backhoe. While the backhoe is digging, plumbers begin to prepare the pipes that will be installed underground. When the trench is complete, plumbers lay the pipe sections into the trench, and connect the sections to form a continuous run. Once the pipe has been installed in the trench, a city testing authority is called to inspect the system.

The degree to which the sub-grade piping system is inspected varies greatly among localities. By code (BOCA, 1998), the system should be filled with water for 30 minutes, and each connection should be checked by a city official for leaks. If this is done, the inspection process for a medium-sized building should take about two hours. However, most city inspectors are extremely busy, and may only spot-check the system (Valante, 1997). Naturally, processing times for inspections vary greatly as a result of this inconsistency in inspection detail.



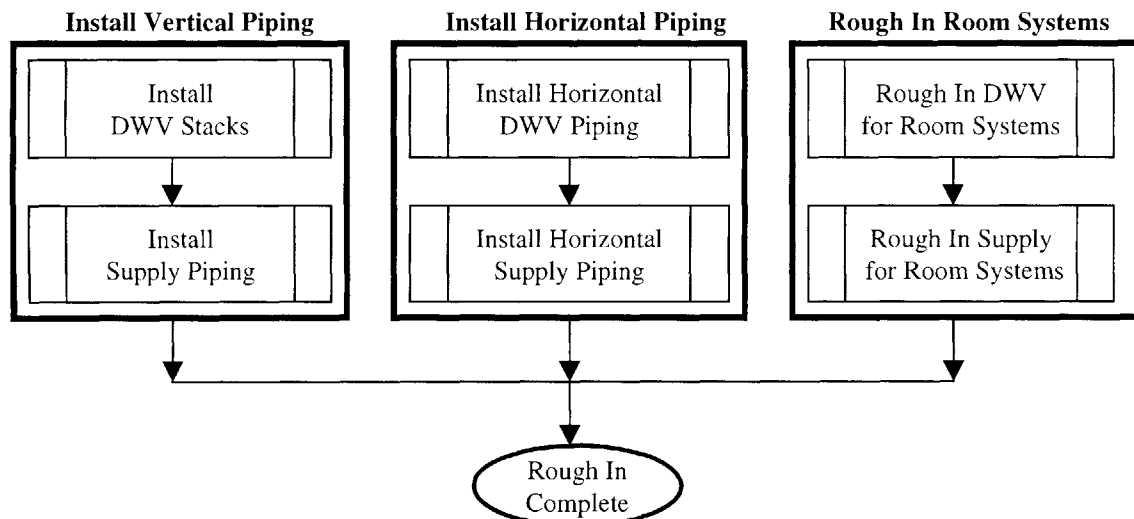
**Figure 4.14: Installation of Sub-Grade Piping**

#### **4.3.2 Rough-In of Water Distribution and DWV Systems**

Plumbing rough-in includes the installation of all DWV and supply piping for a building. In fire protection installation, rough-in includes the installation of all piping up to the point of the sprinkler heads. The process can be further divided into three main areas: 1) Installation of Vertical Piping, 2) Installation of Horizontal Piping, and 3) Rough-In of Room Systems.

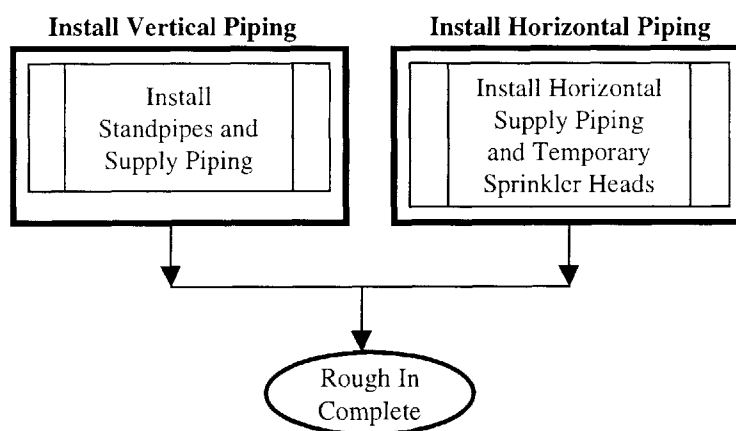
Figure 4.15 illustrates the relationship among the three subprocesses of rough-in for a plumbing system. The processes listed below are not sequentially related, yet they are linked by the fact that horizontal piping feeds off of vertical piping, and leads into the room systems. Usually, plumbers and

pipefitters prefer to install stacks and risers first, then the horizontal plumbing that feeds off of the risers, and finally, the piping for the room systems. But the actual order of the processes depends on the overall progress of the building. If, for example, the structural framing of the upper floors on a tall building have not been installed yet, plumbers may choose to install the horizontal piping and room systems for the lower floor before installing the risers and stacks on the upper floors.



**Figure 4.15: Relationship between the Rough-In Sub-Processes for Plumbing**

The rough-in process for fire protection is similar to the process for plumbing installation. As Figure 4.16 below illustrates though, the room system rough-in process is not included as a separate sub-process, and DWV stacks are not necessary for fire protection systems.



**Figure 4.16: Relationship between the Rough-In Sub-Processes for Fire Protection**

#### **4.3.2.1 Installation of Vertical Piping (Risers, Stacks, and Standpipes)**

The installation order of various vertical pipe elements depends heavily on the progress of the building as a whole. If the floor slabs have already been poured for all of the floors in the building, then plumbers generally prefer to install the entire length of a particular riser before moving on to the next riser (Valante, 1997). But if the upper floors are not ready yet, then plumbers will install all of the risers for a particular floor before moving to the next floor.

In plumbing, a precedence relationship exists between the installation of DWV stacks and the installation of supply risers. DWV stacks are usually much larger in diameter than supply pipes. Also, the pitch requirements for DWV pipes make the exactness of their location critical. As a result, plumbers install the DWV piping for a particular area of stacks and risers before they install the supply risers. In fire protection installation, there is no precedence relationship, because standpipes and risers both supply water.

Figure 4.17 illustrates the installation process for vertical piping. The process is essentially the same for all types of vertical piping, including supply risers, stacks, and standpipes. Usually, a two-person crew will work together to install vertical piping, although only one person is necessary for small diameter risers (less than 1 inch (2.5 cm)).

Floor penetrations for stacks and risers are either placed before the floor slabs are poured (sleeves) or else they are cored out afterwards. Plumbers prefer to install sleeves in the corrugated decking for a floor slab before the concrete is poured, because sleeve installation requires less labor than coring. The exact locations for the penetrations may not be known before pouring the slab, however. In this case, plumbers must use a core-drilling machine (see resource list) to cut penetrations through the slab. Usually, all of the required penetrations for a floor will be cut at one time to minimize movement of the machine.

Pipe sections required for the stacks and risers are delivered by a truck and stored on site while the penetrations are being cut. Following delivery, plumbers begin to prepare the sections and fittings for installation.

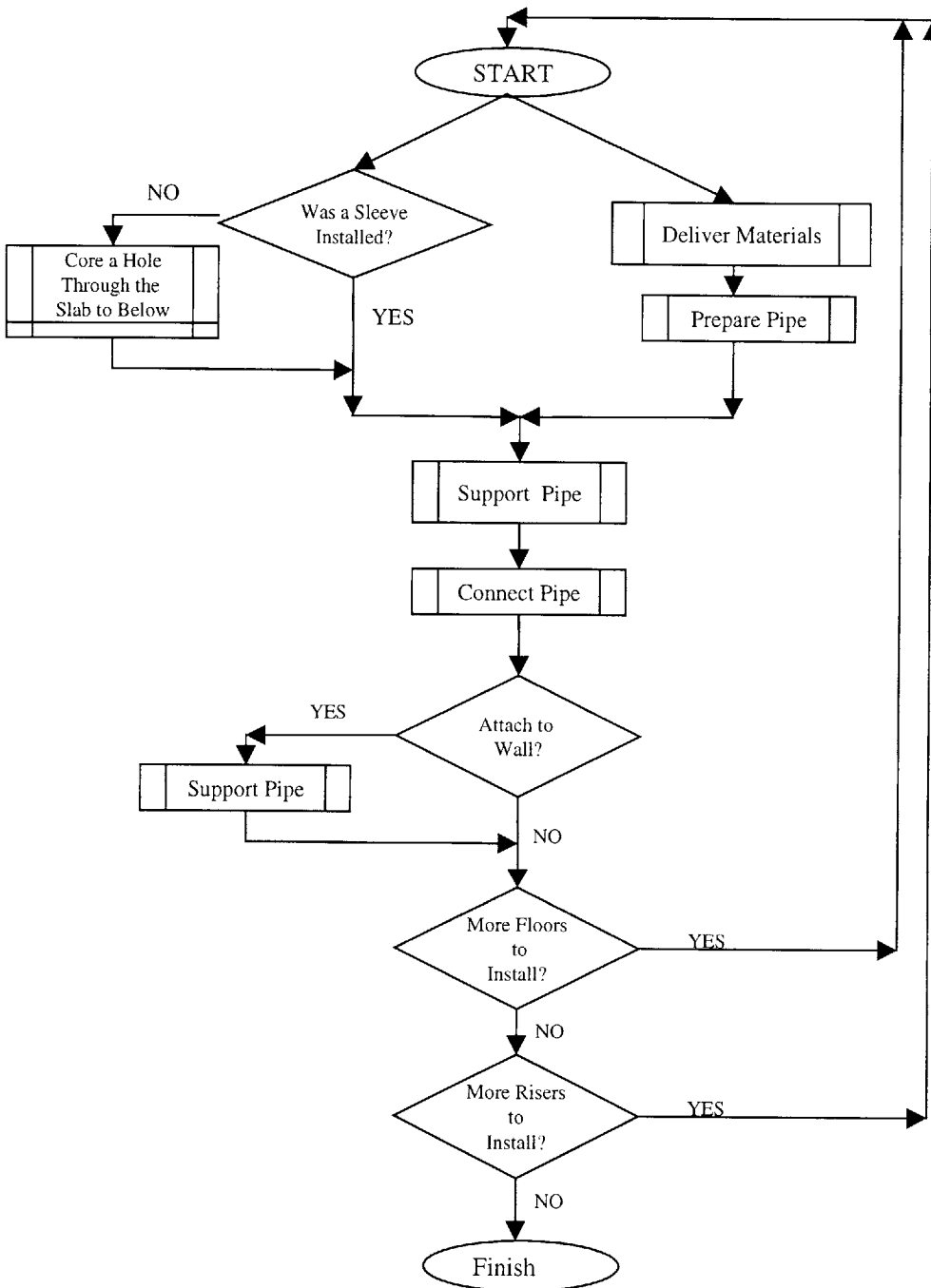
Installation for a particular riser begins by attaching a section of pipe to the floor penetration with a vertical clamp. The clamp serves to support and stabilize the pipe section. For heavier pipe materials, like cast iron, a hoist or chainfall is used to lift the section into place.

Once a section has been supported, a second section is connected to the stabilized section. At this point, the connection process takes place before the pipe is supported. As soon as the connection is made, though, the new pipe section is supported through the use of a pipe clamp (see Figure 4.13).



Usually, one team of workers stands on the floor above to lift the section, while another team guides the section into place and forms the connection.

The installation process repeats for the length of the riser or stack. In cases where the floor-to-floor height is abnormally high (more than 12 feet, or 4 meters), additional wall clamps may be attached to further stabilize the risers (Dowd, 1998).

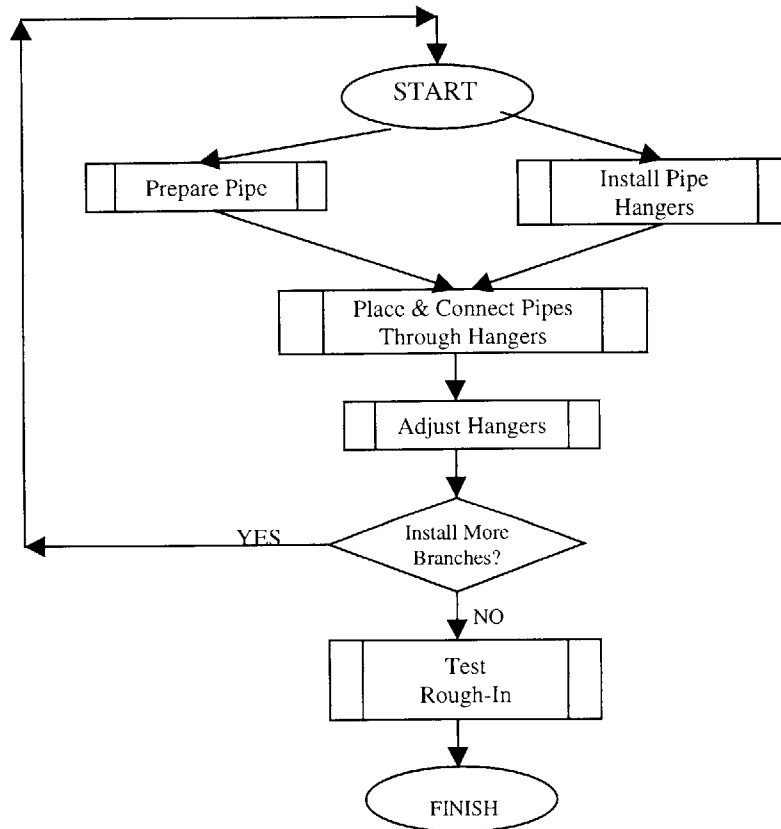


**Figure 4.17: Installation Process for Vertical Piping**

#### 4.3.2.2 Rough-In of Horizontal Piping Runs

Horizontal piping installation is the same for fire protection and plumbing systems, but there is usually a great deal more horizontal piping in fire protection systems. As mentioned earlier, plumbers try to reduce horizontal pipe runs because of the pitch constraints in DWV piping. Similar to the installation of vertical stacks and risers, horizontal pipe installation in plumbing can be divided into DWV and supply installation. Again, DWV piping is installed in a particular area before supply piping.

Figure 4.18 illustrates the process for installing horizontal pipe runs. Coring is not required for plumbing in new construction of commercial buildings, because the plumbing is installed before interior walls are erected. In renovations and residential construction, however, penetrations may have to be cut into pre-framed or existing walls.



**Figure 4.18: Installation Process for Horizontal piping.**

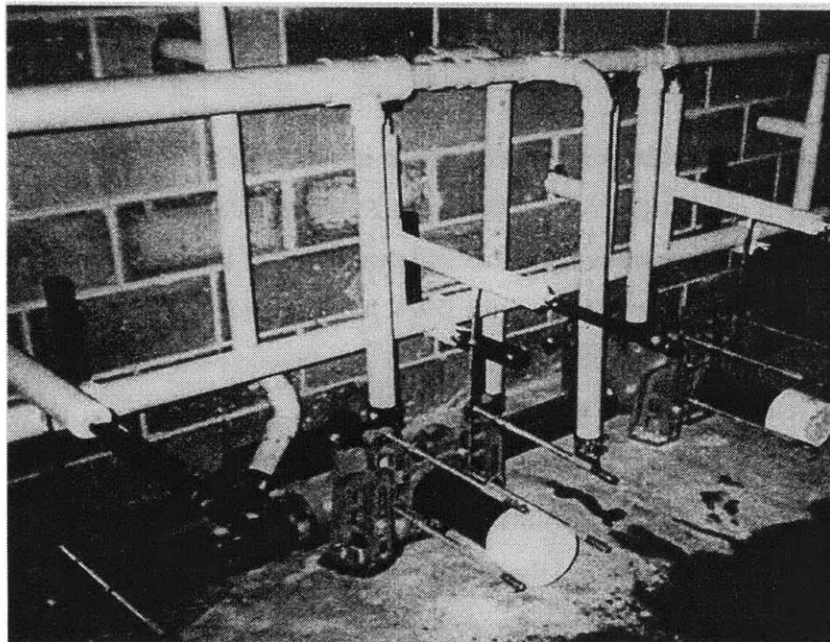
Plumbers usually install horizontal pipe in segments called “runs” (Dowd, Valante, 1998). The runs usually pertain to a branch or main (see Section 4.1), and are generally installed by two-person teams. Often, a two-person team will install hangers for the pipe run well before the actual pipe is

installed. Once the run is measured, the required pipe sections and fittings are collected, and sections are cut if necessary.

Once the hangers are in place, the pipe sections are lifted up to the hangers and connected as described in Section 4.2.2. Plumbers will use ladders or portable scissor lifts to reach the installation level. Once the pipes are connected, they are checked for proper pitch, and the hangers are adjusted accordingly.

#### **4.3.2.3 Rough-In of Room Systems**

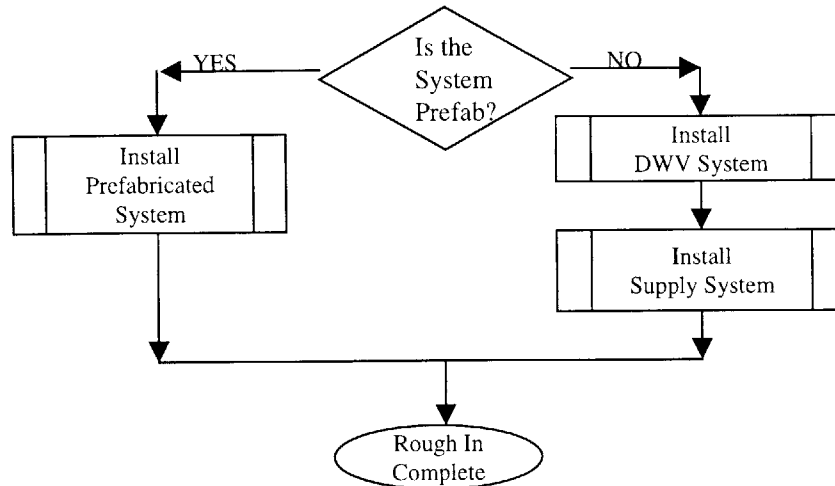
Room systems often require an intricate network of piping that has to “snake” around wall studs and ceiling tiles. Also, supply and DWV piping have a common terminus (a fixture) as they branch out from vertical piping. For these reasons, the process model separates the tasks involved in room system rough-in from the rest of the building. Figure 4.19 illustrates the intricate network of supply and DWV piping associated with the rough-in of a group of fixtures.



**Figure 4.19: Rough-In System for a Group of Water Closets (Wentz, 1998)**

Figure 4.20 outlines the major steps in room system rough-in. Plumbing systems for a room are often prefabricated to a certain degree to reduce labor costs (Dowd, 1997). In some cases, only the DWV piping is prefabricated, but many contractors prefer to prefabricate the supply system as well. For

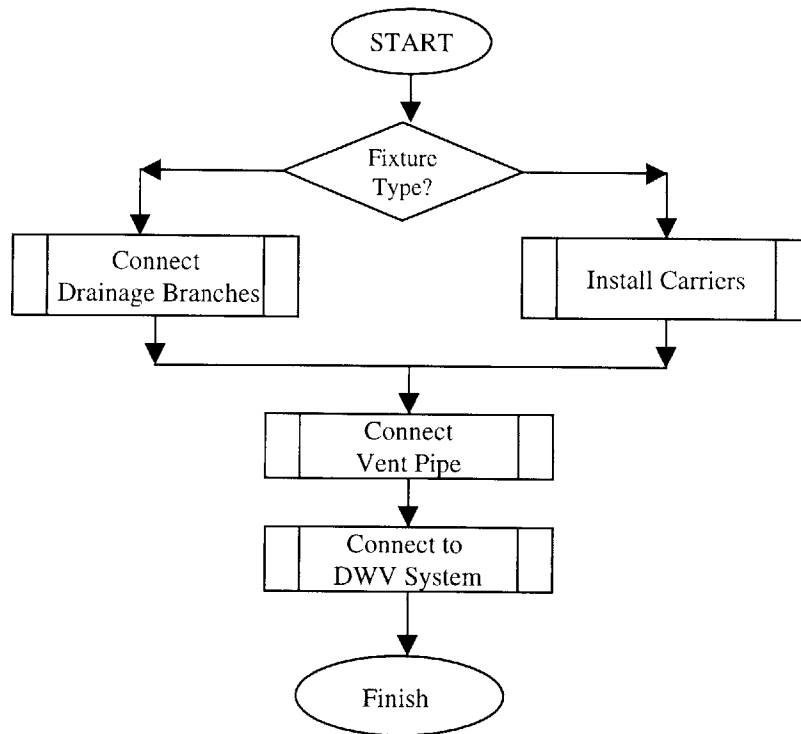
this reason, the process model separates the tasks associated with prefabricated systems from those required for on-site installation.



**Figure 4.20: General Process for Room System Rough-In**

The sub-processes within room system rough-in consist of a combination of the Prepare, Connect, and Support process described in Section 4.2.2. The installation process for the DWV system, for example, involves the preparation, support, and connection of both drain and vent piping associated with each fixture. Figure 4.21 summarizes the DWV rough-in process. The steps are usually performed by one person instead of two, though, since the space in a room system is rather confined, and the pipe sections used are relatively small (Dowd, 1998).

Once rough-in of the building is complete, inspection by a city official is required. The inspection process for rough-in is similar to the process described in section 4.3.1 for Sub-Grade piping. In the DWV system, the pipe network is filled with 10 feet (3m) of head, and each section is inspected for leaks and proper pitch. The supply piping system is filled with either air or water, and the system is pressurized. Each connection is then inspected for leaks under the operating pressure. Appendix A contains flow diagrams for the inspection processes associated with both supply and DWV piping.



**Figure 4.21: Installation Process for DWV Rough-In for a Room System**

### 4.3.3 Installation of Equipment

Equipment can be installed once the room where it will be installed is ready. Usually, the equipment is located in a mechanical room, which may be located on the bottom floor or on the roof. The installation tasks required for equipment varies by type and brand of equipment. Consequently, the process times and resource requirements vary as well. In general, installation steps include delivery, unpacking, and connection to the system. Figure 4.22, an outline of the installation steps for a water heater, demonstrates the equipment installation process.

### 4.3.4 Finish of Plumbing and Fire Protection Systems

Finish work includes the installation of all plumbing fixtures and fire sprinkler heads, and does not begin until the rough-in has been completed. Fixtures can be either floor mounted (e.g., water closets) or wall hung (e.g., most sinks and urinals). Finish work for a particular room cannot begin until

the majority of the interior work, including walls and ceiling tiles, has been completed. Usually, floor tiles and carpeting must be in place as well.

In plumbing systems, stub-outs for supply and drainage piping extend out past the interior walls. Plumbers attach the supply stops and traps for the fixtures directly to these stub-outs. Fire protection systems use similar stub outs that penetrate through the ceiling tiles or walls. Sprinkler heads attach directly to these stub-outs.

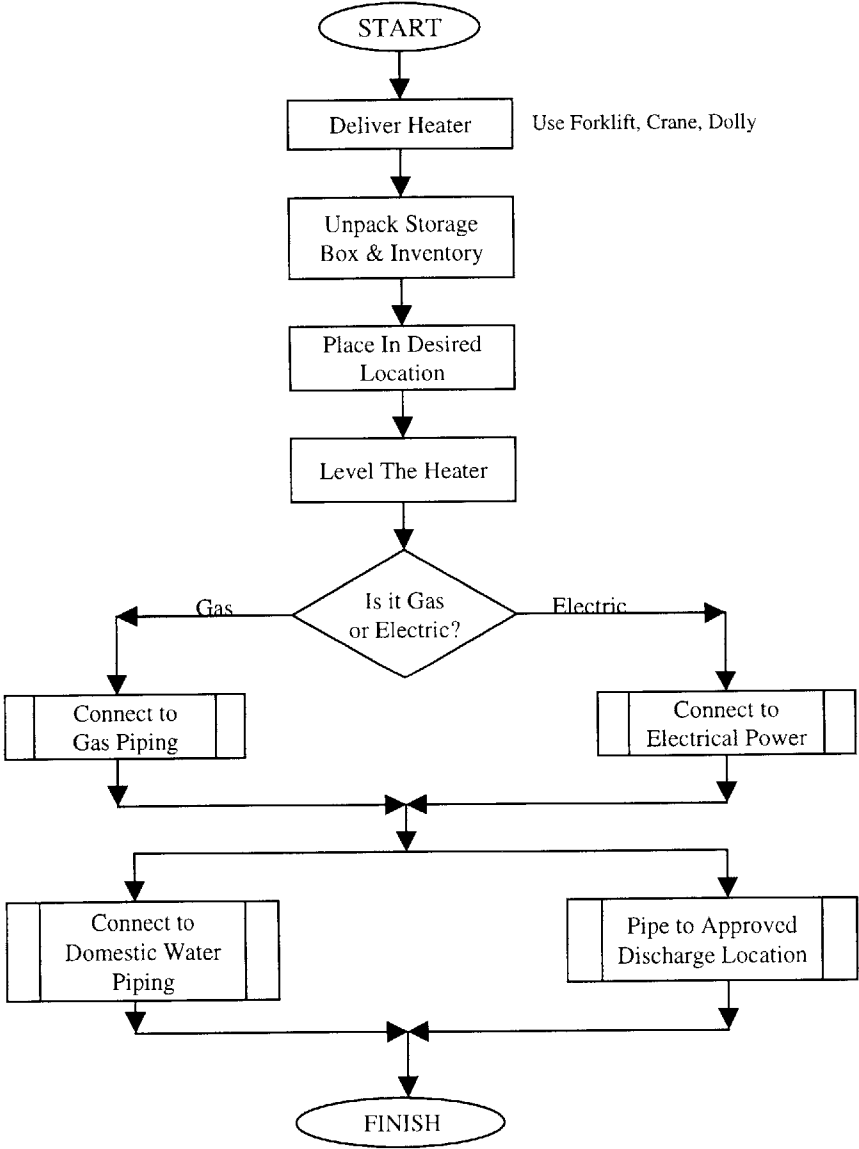


Figure 4.22: Installation of a Water Heater

#### 4.3.5 Testing and Startup

Plumbing and fire protection systems are tested and inspected several times during the installation process. As mentioned earlier, city officials must inspect and approve of sub-grade systems and piping rough-in. Following installation of all fixtures and sprinkler heads, a final test is conducted before turnover of the building to the owner or its agents, and before the building can obtain an occupancy permit. The systems are connected to the street supply and sewer systems, and each fixture is checked for adequate pressure and temperature output. The fire protection system is checked visually to see if the sprinklers are spaced for adequate coverage.

#### 4.4 Resources

The primary resource required for installation of plumbing and fire protection systems is the plumber. Unlike equipment-intensive systems like steel erection and foundation work, the majority of tasks required for plumbing installation can be performed by a one or two plumbers equipped with hand tools.

As demonstrated in earlier sections, plumbing and fire protection crews generally work in teams of two people. Journeymen (highly skilled and experienced craftspeople) perform the majority of the tasks, but foremen (supervisors) help when they are not supervising. Apprentices and laborers will assist the crews with simple tasks like delivering material and installing hangers. Table 4.6 outlines the typical ratio of foremen to journeyman to apprentices, and summarizes the jobs performed by each. Interviews conducted with industry leaders from around the country indicate that crew ratios can vary greatly by job and by region. Labor unions in different areas often have an influence on the ratio of foremen to journeymen to apprentices as well (Howarth, 1998).

General Tasks	Crew Size
(Install DWV Stacks, Critical Risers)	2 Journeymen 1 Foreman Supervises
Install Supply and DWV Runs, Equipment, Room Systems	2 Journeymen 1-2 Apprentices
Install Fixtures	1 Journeyman
Test Systems	1 Foreman, 1 Journeyman
Typical Crew Ratio: Foreman/Journeyman/Apprentice	1 F / 3 J / 3 A

**Table 4.6: Summary of Crews**

Plumbers and sprinkler installers usually carry a box of hand tools to perform the majority of the tasks associated with installation. Table 4.7 below lists the tools that many of the contractors interviewed indicated as common to most plumbers on site.

Tool	Quantity	Use
Wooden Rule, 6 foot	1	Measuring
Tape Measure, 50 ft	1	Measuring
Level, 2 foot and Torpedo	2	Determining Proper Slope
Chisels	4	Cutting Pipe, Removing Slag
Plumb Bob	1	Vertical Alignment for Risers
Roller Pipe Cutter	1	Cutting 2" or less pipe
Slip-joint Pliers	2	Tightening Joints
Pipe Wrenches	2	Tightening Joints
Flaring Tool	2	Flaring Copper Pipe
Swage Tools	4	Swaging Copper Pipe
Torque Wrench	1	Tightening Joints
Compound Wrench	1	Tightening Joints
Hammer	1	Miscellaneous
Hammer Drills	1	Miscellaneous
Hacksaw	1	Cutting Materials
Cut-off Saw	1	Cutting Plastic and Threaded Pipe
Pipe Tap	1	Cutting Internal Threads
Pipe Reamer	1	Remove Burrs
Propane Torch	1	Soldering
Flux	1	Soldering
Solder	1	Soldering
Small Brush	1	Soldering
Cloth	1	Cleaning Joints

**Table 4.7: Hand Tools Carried by Plumbers/Sprinkler Installers**

Some larger equipment may be required for handling larger section of pipe or pieces of equipment. Plumbing and Fire Protection contractors may own the large equipment themselves, or they may lease it from either a supplier or the general contractor (Sacchetti, 1998). Table 4.8 lists some of these larger resources, as well as their use for installation.



Tool	Quantity	Use	Who Provides
Core-drilling Machine	1	Bore holes through slabs	Plumbing Contr.
Roll-Grooving Machine	1	Roll Grooves for Victaulic Fittings	Plumbing Contr.
Pipe Threading Machine	1	Threading Pipe	Plumbing Contr.
Portable Power Drive	1	Threading Pipe	Plumbing Contr.
Vise Stand and Chain Vise	1	Hold Pipe for Cutting, Threading	Plumbing Contr.
Yoke Vise	1	Hold Pipe for Cutting, Threading	Plumbing Contr.
Soil Pipe Cutters	2	Cut Cast Iron Pipe	Plumbing Contr.
Portable Scaffolding	1	Elevate Workers	Plumbing Contr.
Come-Along Cables	1	Hoisting Equipment	Plumbing Contr.
Chain Falls	1	Hoisting Equipment	Plumbing Contr.
Oxygen Tanks	2	Welding	Plumbing Contr.
Acetylene Tanks	2	Welding	Plumbing Contr.
Crane		Lifting Equipment/Supplies	Varies w/Job
Scissor Lifts	2	Work in High Areas	Plumb.Contr. Rents
Forklifts		Transporting/Lifting Equipment	GC provides
Power Drills	2	Drilling Small Holes	Plumbing Contr.

**Table 4.8: Larger Equipment used on Site**

The production rates of crewmembers and equipment vary with the complexity of the task and the experience of the crew. Table 4.9 highlights the approximate production rates of plumbers and pipefitters for some of the major installation processes (as derived from site observations, described in Chapter 3).

#### 4.5 Safety Issues

Compared with other systems such as steel erection, plumbing installation is relatively safe. There are, however, some safety issues that place constraints on the process. Government regulatory agencies such as the Occupational Safety and Health Agency (OSHA) and trade unions mandate certain safety regulations to protect their members.

The trenching model for sub-grade pipe installation demonstrates the impact of regulations on the process. OSHA mandates that shoring be installed for any trench deeper than three feet (Dowd, 1997) to protect workers against a cave-in. The additional tasks required for shoring installation adds time to the overall process.

Common to the construction industry as a whole, any work done over a height of 6 feet (2m) requires a stable scaffold or fall protection devices. Most horizontal plumbing for commercial buildings is done at heights over six feet, so this regulation has significant impacts on the installation process (Sacchetti, 1998). Pipe installation may also involve exposure to open flames (soldering) or toxic

chemicals (PVC pipe). Protection devices, including gloves, masks, and respirators are required in these cases to protect the installer.

As mentioned in Section 4.2.3, installation of vertical piping may require coring of existing floor slabs. When coring is required, a temporary barrier must be placed on the floor below to prevent workers below from being injured. The additional tasks required for safety measures like these can add time to the overall installation process.

Task	Resources	Production Rate
Install Below-Grade Plumbing	Crew - 1 Foreman, 2 Plumbers Equipment- Backhoe, Pipe Cutters	2 Weeks, Including Inspection and Backfill for a 10,000 Square Foot (1015 m <sup>2</sup> ) Footprint
Install DWV Stacks	Crew - 1 Foreman, 2 Plumbers Equipment - Chainfalls, Scissor Lifts, Pipe Cutters, Core-Drilling Machines	2 hours per Floor, per Stack
Install DWV Runs	Crew - 2 Plumbers Equipment - Scissor Lifts Pipe Cutters	No-hub - 40 Feet(13 m)/Day PVC - 50 Feet(15 m)/Day
Install Supply Runs	Crew - 1-2 Plumbers Equipment - Scissor Lifts Pipe Cutters	Copper Pipe - 50 Feet(15 m)/Day PVC - 60 Feet(18 m)/Day
Rough-In Bathroom	Crew - 1-2 Plumbers Equipment - Power Drill, Core Drilling Machine, Pipe Cutters	3 hours per fixture
Install Mechanical Equipment	Crew - 1-2 Plumbers	Gas Heater - 1 day (8 hours) Electric Heater - 5 hours Pump, 3" - 1 day (8 hours)
Install Fixtures	Crew - 1 Plumber	Water Closet - 2 hours Urinal, Wall Hung - 3 hours Lavatory - 2 hours Bathtub - 2 hours

**Table 4.9: Production Rates**

## 4.6 Summary

The complete set of tasks and sub-processes, as well as their associated production rates, for plumbing and fire protection installation processes can be found in Appendix A. The production rates of human beings are more difficult to predict accurately than the rates for a piece of equipment (a bulldozer, for example). Since most of the tasks in plumbing and fire protection installation are

performed by people, the variety in production rates can have a significant impact on the overall process time predicted by the process model.

As mentioned earlier, plumbers must often work around the installation of other systems. The specific physical tasks required for installation are captured in the model, but many “real-world” issues are not. For example, the model does not account for the time plumbers must spend plotting the route of the room system plumbing, or the time they must spend coordinating with members of the other building trades. It is important to remember, though, that the purpose of this model is to simulate the actual value-added tasks associated with installation. Delays and disruptions can easily be added to the model to account for the coordination issues that arise from working with other trades. The models developed in the next chapter can therefore obtain a general sense of the vulnerabilities to disruptions while they focus on the savings in time and improvements in safety that result from changes in process or design specifics.



## 5 Modeling the Installation of Plumbing and Fire Protection Systems

Chapter 4 summarized the general processes associated with plumbing and fire protection installation. The processes have been characterized by hierarchical charts which, when combined with the resource and design specifics and structured to reflect overall project progression, form the complete dynamic process models. The complete sets of flow diagrams for both models are listed in Appendix A.

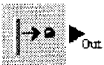
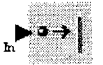
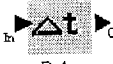


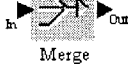
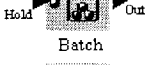

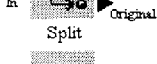
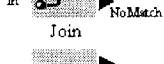

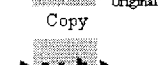
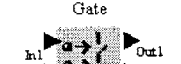
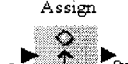




Once the models had been established and verified by industry members, their accuracy was tested through a computer simulation. SIMPROCESS® was used to convert the flow charts into computer-based dynamic process models that could be modified and edited to adapt to the unique design and process specifics for any particular plumbing or fire protection project. The results of the computer-based model were reviewed by specialty contractors, and were found to accurately reflect current costs and duration for the installation of plumbing and fire protection systems.

### 5.1 Fundamentals of SIMPROCESS®

SIMPROCESS® is a hierarchical, computer-based simulation environment (CACI, 1996) that can be used to develop dynamic process models. It is object-oriented, and allows the user to create reusable templates from its basic collection of built-in activities. The basic collection of activities consists of 18 different activities, which are summarized in Table 5.1 below. SIMPROCESS uses icons to represent these built-in activities.

The activities listed above are connected to form a template for a process. These process templates can be arranged hierarchically to allow the user to decompose the installation process into as many levels of detail as necessary.

SIMPROCESS is driven by the flow of *entities* through the hierarchical network of process activities described above. Entities are people, materials, components, or information that flow through the model and have work performed on them as they pass through particular activities. They can be produced by an activity, or they can be defined at the start of the simulation. The characteristics of an entity, called attributes, determine the entity's path through the model. The user can either input attributes at the start of the model or else allow the model to assign attributes to an entity as the entity passes through activities. SIMPROCESS's ability to modify entity attributes inside the model gives the program the flexibility to respond to the dynamic nature of construction activities.

Creates the entities which flow through the model.			Disposes of entities when they are no longer required in the model.
Represents any activity requiring time to complete.			Assembles a new entity from specified components.
Represents decision branches within the model.			Merges several different entity flow paths together.
Establishes a group of entities which can be ungrouped elsewhere in the model.			Ungroups a batched entity into its component entities.
Separates an entity into a parent and a number of children that can be reunited at some later time.			Reunites parent and children entities that were created in a split.
Transforms one type of entity into another.			Makes identical copies of incoming entities.
Holds a number of entities back until a release is triggered.			Used to make the assigning of entity attributes explicit in the model.
Synchronizes the release of two or more different entities.			Replenishes resources that may be used up over the course of a simulation.
Used to acquire one or more resources for a set of activities.			Used to free one or more resource previously acquired at a "Get Resource" activity.

**Table 5.1: SIMPROCESS Activities (Carr, 1998)**

## 5.2 Description of Entities

As mentioned in the previous section, entities flow through the hierarchical network of activities in a dynamic process model. They can represent information, people, components, or materials. For the models developed here, entities represent the materials and components that have work performed on them to create a plumbing or fire protection system.

The entities' size and characteristics need to be as small as possible to be flexible enough to accommodate the detailed nature of the processing activities. The model should also be "user-friendly," though, so the entity should be a unit that the user can easily identify and put into the model. Finally, the path of a particular entity is determined by the entity's attributes, so the attributes must be detailed enough to ensure that all of the necessary activity-related characteristics are captured. To accomplish these goals, five entities were created: mains, branches, risers, fixture groups, and equipment pieces.

### ***Mains and Branches***

The primary entities flowing through the models are *mains* and *branches*. As described in Chapter 4, mains refer to horizontal runs of pipe that feed off of risers, and branches feed off of the mains to terminate in a fixture or sprinkler head. The branch as an entity is small enough to capture all of the unique attributes of a run of pipe without being redundant. Attributes such as length, material, and connection type are consistent along a branch, so the user can input the attributes one time for the entire branch. Table 5.2 lists the attributes of a main or branch that determine its path through the model.

The branch and main entities can be inferred easily from a set of drawings, because they represent units that plumbers and designers understand and work with in practice. The attributes listed in Table 5.2 represent the characteristics that plumbers and designers consider when planning or installing a system.

Branches and mains reflect a unit of work by which many plumbers organize their activities (Valante, 1997). Based on the observations conducted for this research, plumbers often install pipe runs in a sequence of branches or mains. In the installation of a horizontal fire protection branch, for example, plumbers may install the mains for a floor, and then come back and install the branches that feed off of each main (Dowd, 1998).

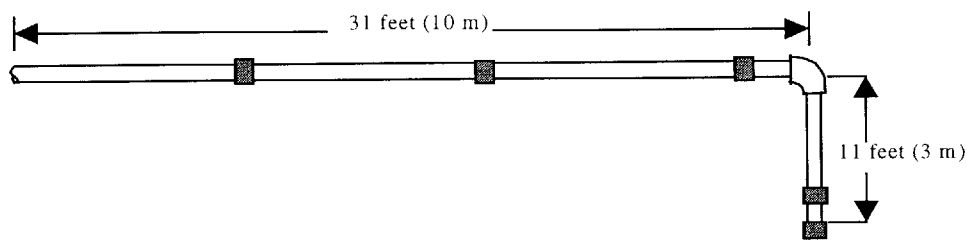
Attribute	Type of Attribute	Description
Length	real number	Total Length of the Entity (feet)
Material	string	Pipe Material (copper, steel, etc.)
SectionLength	real number	Length of Pipe Sections Used (feet)
ConnectionType	string	Type of Connections Used (soldered, threaded, etc.)
Height	real number	Height of the Pipe Run (feet)
NumberOfLegs	integer	Number of Straight-Line Portions in the Run
NumberOfBranches	integer	Number of Pipes Branching off (Mains only)
NumberOfConnections	integer	Number of Connections Needed to form the Run
NumberOfCuts	integer	Number of Pipe Sections that must be Cut
NumberOfWholeSections	integer	Number of Whole Pipe Sections Used
SystemType	string	Plumbing System (supply or DWV)
HangerType	string	Type of Hanger Used to Support the Run
HangerSpacing	real number	Spacing required between Hangers
RiserNumber	integer	Riser from Which the Main or Branch Originates
FloorNumber	integer	Floor that the Main or Branch is on

**Table 5.2: Main and Branch Attributes**

Several of the attributes listed in Table 5.2 can be derived from the overall length of the branch or main. The number of connections, for example, can be determined by dividing the total length of the

leg by the length of the pipe sections used. For mains, additional connections that result from branches that spur off of the main are captured in a separate attribute that counts the number of branches associated with the main (Number of Branches). If the main or branch has turns (Number of Legs), the additional connection and pipe cut required at the elbow is added to the “Number of Connections” and “Number of Cuts” attribute respectively.

Figure 5.1 below shows an example of the calculations used to determine various attributes of a copper pipe branch. The branch consists of two straight-line legs connected by an elbow. The legs total 43 feet (13m) in length.



- Number of Connections = Total Length/Section Length + Number of Legs  

$$= (44 \text{ feet}) / (10 \text{ feet}) + 2$$

$$= 6 \text{ (round down for connections)}$$
- Number of Whole Pipe Sections = 4
- Number of Cut Pipe Sections = 2 (additional length past sections for each leg)

**Figure 5.1: Calculations Used to Determine Entity Attributes**

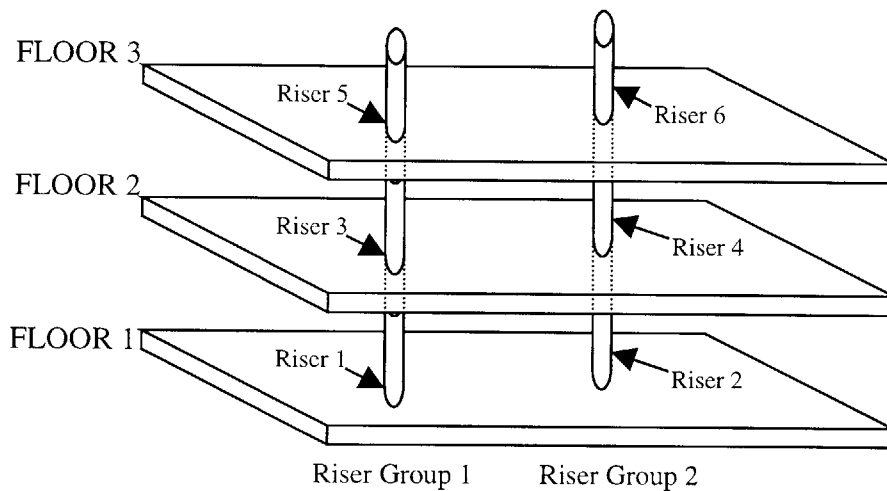
### ***Risers***

Risers refer to vertical runs of piping. Because they are vertical, risers can extend through several floors. For simulation purposes, however, a riser only spans the height of one floor; the computer model considers a riser’s extension into another floor as a separate riser. The floor-height limitation was chosen to capture the installation process for a riser more accurately and flexibly. As described in Chapter 4, plumbers either install risers by floor or by riser. Their option is usually dictated by the progress of other building systems. For example, if the risers extend through several floors, but higher floors have not yet been poured, plumbers will install the vertical piping only for the floor that is available, and will install upper-floor portions at a later date. In this case, work for a particular riser is



broken down into floor segments. An entity unit that only reflected entire spans of risers would be unable to capture this segmentation by floor.

Although risers are segmented by floor in the computer model, it is still useful to know the building riser of which a particular riser segment is a part. Mains, branches and fixtures are all serviced by risers, so a particular group of fixtures cannot be considered complete until the riser that feeds them are complete. In order to monitor the progress of all entities associated with a particular riser, an entity attribute called “Riser Group” is used. The Riser Group refers to the entire vertical extension of piping that covers all of the floors. Thus, each riser entity is a segment of a riser group that extends throughout the height of the building. Figure 5.2 shows how risers belong to riser groups and floors for a building.

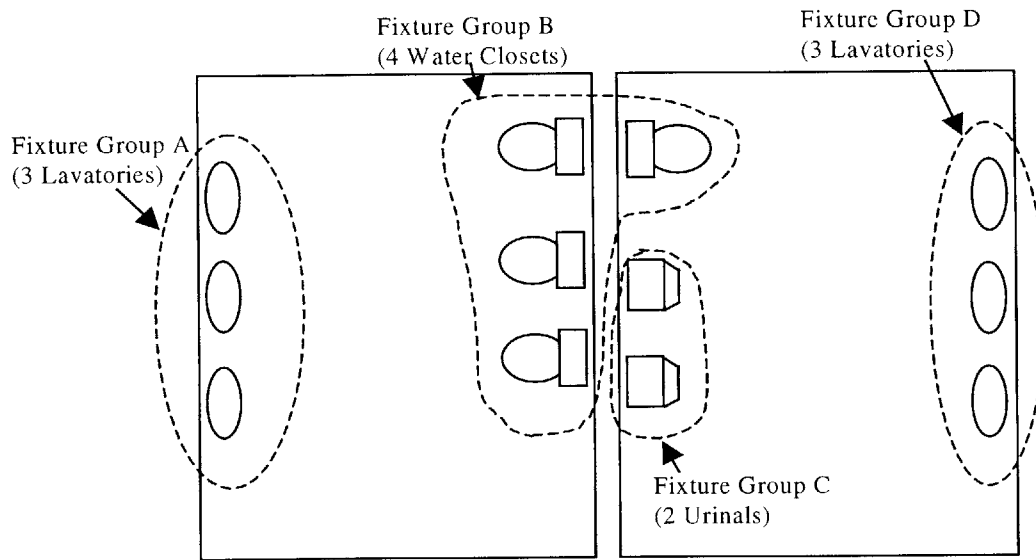


**Figure 5.2: Relationship Between Risers and Riser Groups**

### ***Fixture Groups***

Fixture groups refer to a collection of similar fixtures connected by a network of pipes and supports. For example, a row of sinks in a bathroom is considered a fixture group. Each type of fixture group has specific rough-in and finish activities associated with it, and the activities are repeated based on the number of fixtures that belong to the group and the common attributes of the fixtures in the group.

Figure 5.3 shows how the fixtures are aggregated in the model. In this case, Fixture Groups A and D refer to a set of three counter top sinks, Fixture Group B refers to a set of four water closets, and Fixture Group C refers to a set of two urinals.



**Figure 5.3: Fixture Groups**

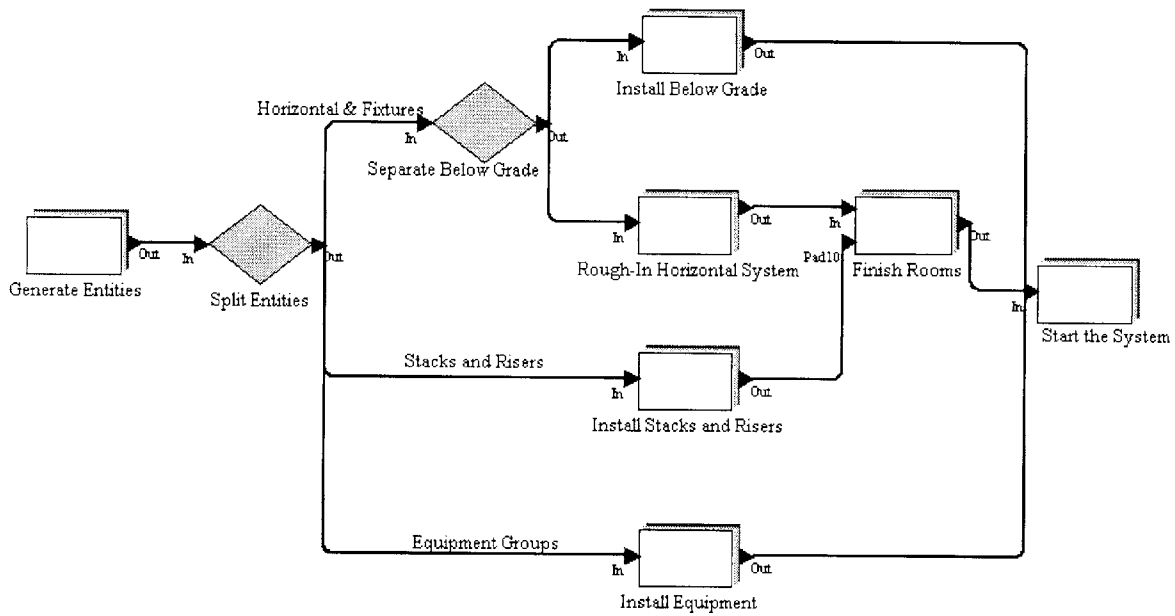
### ***Equipment Groups***

Equipment groups refer to the large pieces of equipment that are installed to power and regulate a plumbing or fire protection system. Similar to fixture groups, equipment groups consist of similar pieces of equipment that share the same installation activities. Heaters, service meters, backflow preventers, and pumps are examples of categories of equipment groups.

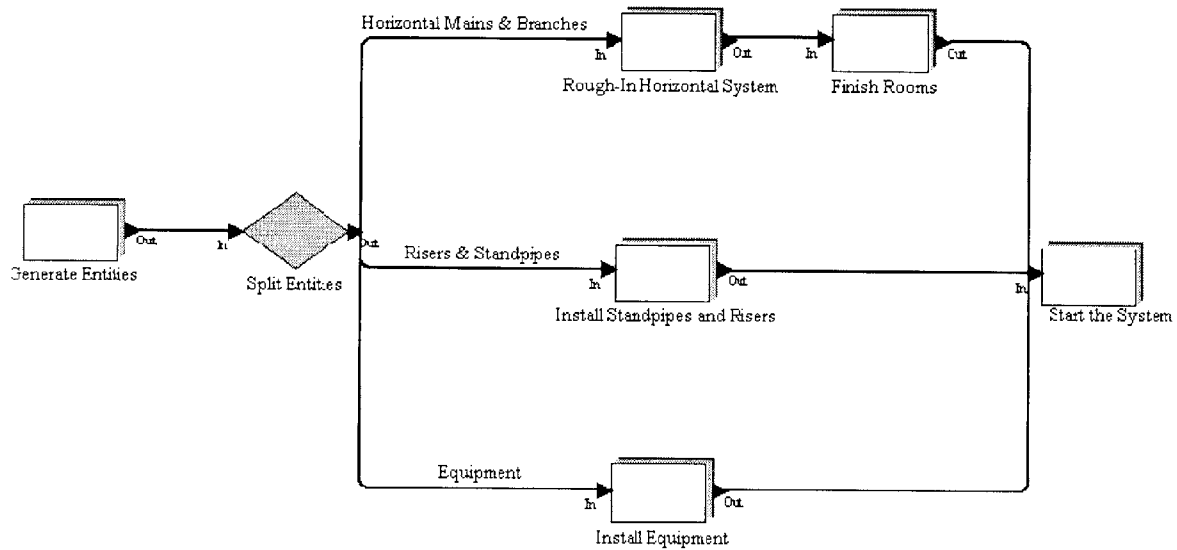
## **5.3 Model Development**

The plumbing and fire protection computer simulation models developed in SIMPROCESS satisfy the objectives described in Chapter 1. First, they accurately reflect the actual installation processes in terms of duration, resource usage, and the logical flow of activities. Secondly, the models are flexible enough to respond to changes in design specifics and process dynamics.

Figures 5.4 and 5.5 show the overall installation processes for plumbing and fire protection respectively. The simulation models are designed to mirror the processes shown in Figure 4.5 with the addition of a separate sub-process that SIMPROCESS uses to generate the entities that will flow through the model. The rectangular boxes represent process templates for the various sub-processes associated with installation. Decision diamonds are used to send the entities through the correct sub-process, based on the entities' attributes.



**Figure 5.4: Overall Computer-Based Process Model for Plumbing Installation**



**Figure 5.5: Overall Computer-Based Process Model for Fire Protection Installation**

### 5.3.1 Generation of Entities

Design specifics for a particular installation system are collected in Excel™-based spreadsheets that are read into the simulation model to assign attributes to each entity that will flow through the model. From Figure 5.5, Process A (“Generate Entities”) contains a series of sub-processes that are used to read the data charts from the data files and then to convert the data into attribute-specific entities. Once the entities have been generated and corresponding attributes have been assigned, the entities begin to flow through the model. Figure 5.6 shows the “Generate Entity” process.

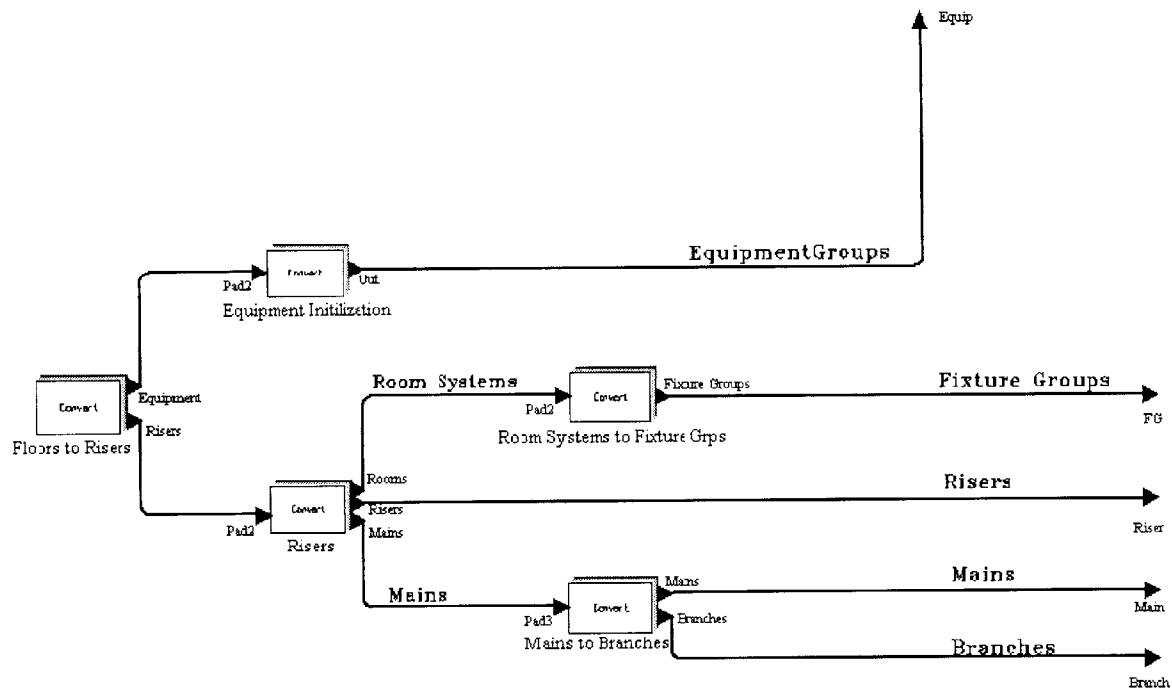
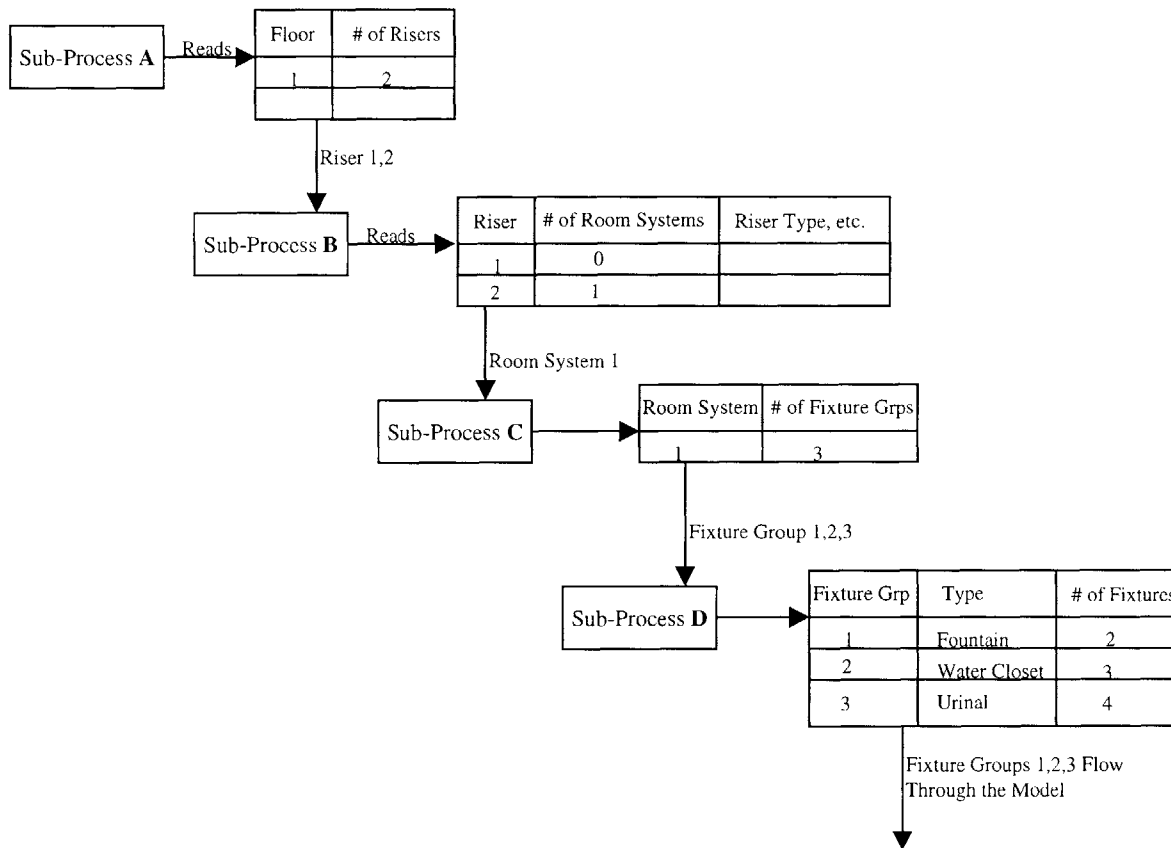


Figure 5.6: Entity Generation Process

The hierarchical information collection system used to generate entities allows the user to input design specifics without having to edit or alter the computer program. Also, as the design becomes more definite, the user can input information at increasing levels of detail. Figure 5.7 illustrates the hierarchical information network used to model design specifics. Information is first collected at the building level, and then progresses down to information specific to a particular entity. The first sub-process reads a data table that lists the number of risers that belong to a particular floor. For each particular riser, the simulation model then reads separate charts that contain riser-specific information. For example, included in the riser information is the number of mains and room systems that are serviced by the riser. The pattern follows at the main and room system level, where information about

each main and room system is collected from a separate chart. Additional charts are read for every branch that feeds off of each main, and for every fixture group that belongs to each room system. The generation process culminates in a collection of branches, mains, fixture groups, risers, and equipment groups. Each entity carries attributes that describe which floor, riser, and room system or main from which the entities' attributes were derived.



**Figure 5.7: Hierarchical Generation Process for Fixture Groups**

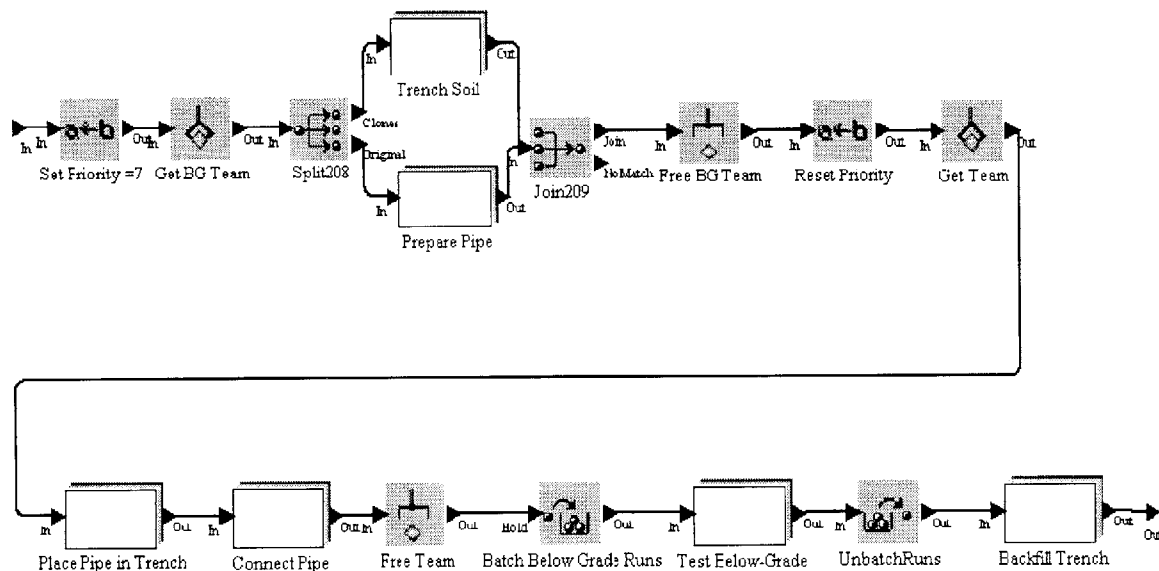
In this example, the number of risers for the first floor, “2”, is read by process A. Each riser entity then flows through process B to read the number of room systems that are serviced by that riser (“0” and “1”, respectively). Next, a temporary entity, a room system, is created for each room system found in process B (1 room system). The room system entity then flows through process C to read the number of fixture groups that belong to that particular room system (“2” fixture groups). A separate entity is then created for each fixture group, and the fixture groups flow through process D to gather fixture group-specific attribute data (type, number of fixtures, etc.). The fixture group is then ready to

flow through the appropriate processes in the simulation model. Appendix B contains the complete collection of spreadsheets used for the prototype building for both the plumbing and fire protection models.

### 5.3.2 Sub-Process Organization

The activities and processes in the simulation models were arranged to mirror the flow diagrams described in Chapter 4 and Appendix A. Similar to the flow diagram, the models consist of a hierarchical network of standard installation activities that serve as the “building blocks” for the overall model. In this case, the sub-process “Install Below-Grade Piping” (Figure 5.8) is broken down into a set of sub-processes. Each sub-process box has its own set of activities imbedded inside. The sub-process “Trench Soil,” for example, consists of a set of activities including “Mark Soil,” “Install Shoring,” and “Trench.”

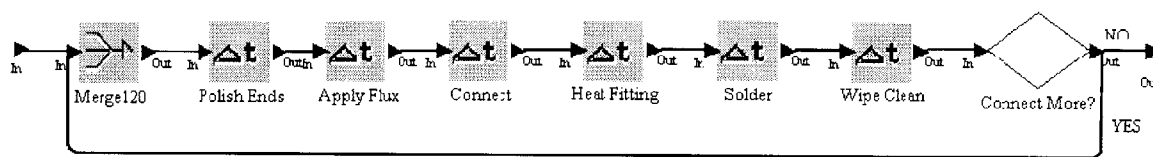
Although the computer simulation program is capable of modeling the hierarchical relationship among installation processes, slight modifications to the links between the processes and activities are necessary to ensure compatibility with the flow diagrams. Counters, gates, decision branches, and priorities are used in the simulation models to accurately reflect the relationship among the major tasks involved in both plumbing and fire protection installation.



**Figure 5.8: Installation Process for Below-Grade Piping**

### Counters

Counters are used when an activity must be performed multiple times on a particular entity. For example, a branch of pipe may require 4 connections. Once the branch passes through the connection process the first time, a counter determines if any more connections are required (see Figure 5.9). The counter reads an entity attribute, called “Number of Connections,” and then knows to send the branch through the process three more times before the branch can move to the next activity.



**Figure 5.9: Use of a Counter for Connecting Pipe Sections**

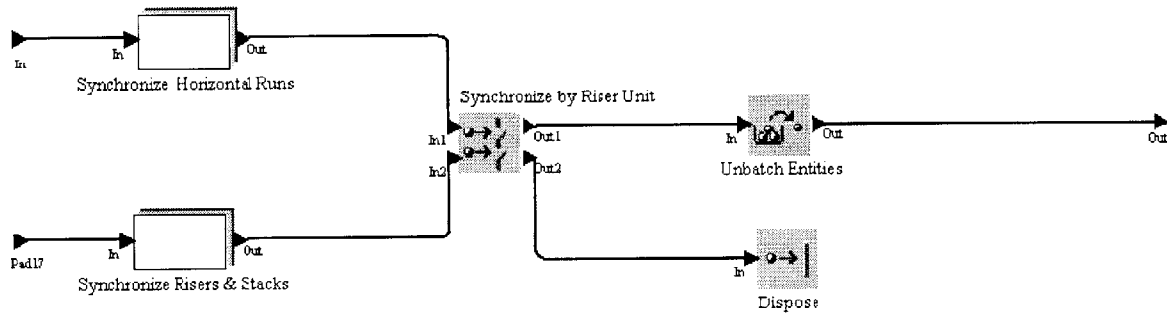
### Gates

Gates ensure that sequential relationships in plumbing and fire protection installation are reflected accurately in the computer model. The gate activity accumulates entities until some number of entities have been received or until a signal is received from another activity to release entities (CACI, 1996). For example, fixtures are not installed in a room until all of the associated plumbing that serves that fixture has been roughed-in and tested, including the risers and stacks that service the fixture group. Figure 5.10 shows how the computer model captures this relationship among activities.

Each entity is assigned a “Riser Group” attribute that assigns the entity to the riser that supplies it (see 5.3.1). A water closet, for example, has a particular riser that feeds it through a main or branch. Once all of the entities (mains, branches, and fixture groups) that belong to a particular riser have been roughed in, finish work on associated fixtures may begin.

The computer model tracks and organizes the progress of each set of entities that belong to a particular riser through *model attributes*. Model attributes do not belong to any particular entity, but they can be used to edit entity attributes on a model-wide level. The entities in Figure 5.10, for example, line up at the gate until all entities associated with the riser are complete. At that time, a model attribute, (called “Riser Group Counter”) allows all entities associated with the completed riser to pass through the gate. The model attribute is then increased by a value of one. Entities associated with

the new model attribute value are then allowed to pass through the gate when their riser group is complete.



**Figure 5.10: Use of a Gate to Synchronize Entities by Riser Unit**

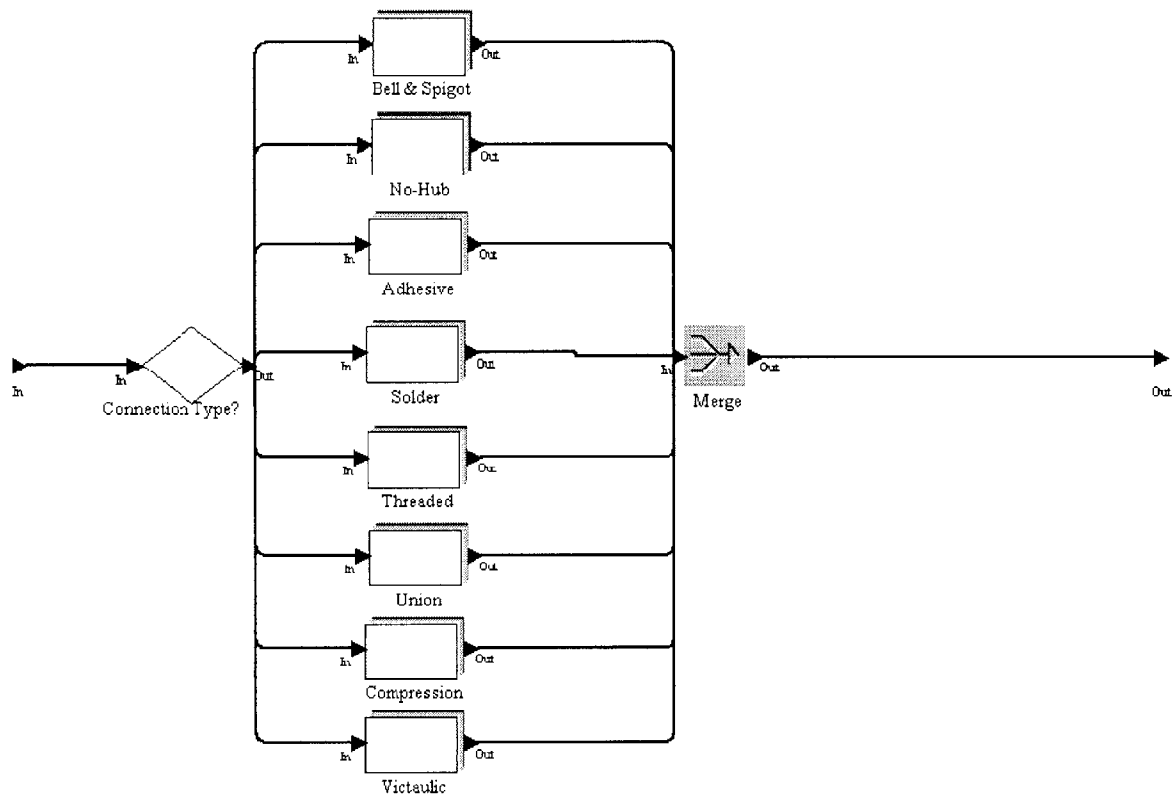
### ***Decision Branches***

Decision branches are similar to the decision diamonds used in the flow diagrams. SIMPROCESS uses decision branches to route entities through different paths of the process model, based on the entities' attributes. In the activity "Connect Pipe" (Figure 5.11), for example, a decision branch is used to route the entity to the proper connection sub-process, based on the entity's attribute "Connection Type." Decision branches can route entities based on entity attributes, entity types, or probability distributions.

### ***Priorities***

Plumbing and fire protection installations are flexible processes, in that the sequence of activities can work around the progress of other systems quite easily. As mentioned in Chapter 4, however, plumbers still prefer to prioritize certain activities whenever possible to optimize their time on site. For example, assuming there are no outside constraints, many plumbers prefer to first install risers, then mains, then branches, and finally fixture groups (Valante, 1997). The simulation model allows the user to simulate these types of specific installation priorities by assigning a "Priority" attribute to entities. If entities are competing for a resource (e.g., a riser and a branch are competing for a plumber), the entity with the highest priority will use the resource first.





**Figure 5.11: Connect Pipes Decision Branch**

### 5.3.3 Resource Sharing

SIMPROCESS simulates resource usage by storing resources in a “pool.” When an entity arrives at a processing activity, certain resources may be required to perform the activity (e.g., plumbers, backhoes). SIMPROCESS removes the required resources from the pool and assigns them to the activity. Once the activity is completed, the resources are returned. If an activity requires a resource that is not currently in the pool, then the activity is not performed until the required resource becomes available.

The primary resource required for plumbing and fire protection installation is people (see 4.3). In fact, most pipe installation activities, including preparation, connection, and supporting of pipes, simply require two crewmembers and a minimal set of tools (pipe cutters, ladders, etc.) Some tasks may require larger equipment like backhoes (trenching) or scissors-lifts (high-level installation), but the equipment is seldom required on a continuous basis throughout the plumbing installation process.

Over 10 different resources were used in the installation models. Plumbers were either assigned to activities on an individual basis, or as part of a team. The plumbers' hand tools (wrenches, hammers, etc.) were not listed as separate resources, because the model assumes that each plumber has his or her own set of hand tools. Table 5.3 below summarizes the different resources used throughout the model.

**Table 5.3: Model Resources and Their Primary Uses**

Resource	Primary Uses
Foreman	Supervise the crew
Journeyman	Performs the majority of tasks
Apprentice	Perform smaller, supervised tasks
Inspector	Inspect the system at various stages
Core-Drilling Machine	Core holes through floor slabs
Table-Sized Pipe Cutter	Cut large pipe sections
Roll-Grooving Machine	Cut grooves into pipe ends
Ladder	Used for elevated installation work
Hoist	Used to lift heavy pipe sections into place
Scissor Lift	Used to elevated installation work
Backhoe	Dig trenches for sub-grade piping
Pipe Threader	Cut threads into pipe ends
Forklift	Lift heavy equipment or pipe sections

As mentioned earlier, installation tasks are generally divided into units that correspond to the entity sizes chosen for the model (branches, mains, risers, etc.). At the entity level, most activities can only be performed at a certain rate, regardless of how many resources are available for work. For example, a typical branch installation requires two plumbers. Additional plumbers could not reduce the time required to connect the sections of the branch, because the connections must be placed in sequence. For this reason, a team of plumbers is assigned to install the branch at the beginning of the installation process, and that team stays assigned to that branch through both the connection and support processes. Figure 5.12 shows how the plumbers are assigned to a particular branch prior to the connection portion of an installation process, and they remain with the entity until support has been completed.

In cases where additional resources can actually reduce processing time, resource requirements are assigned at the individual activity level. In pipe preparation (Figure 5.13), for example, additional plumbers could help cut and measure pipe sections for a branch more quickly. To simulate this, plumbers are assigned on an individual basis for each entity passing through the pipe preparation process.

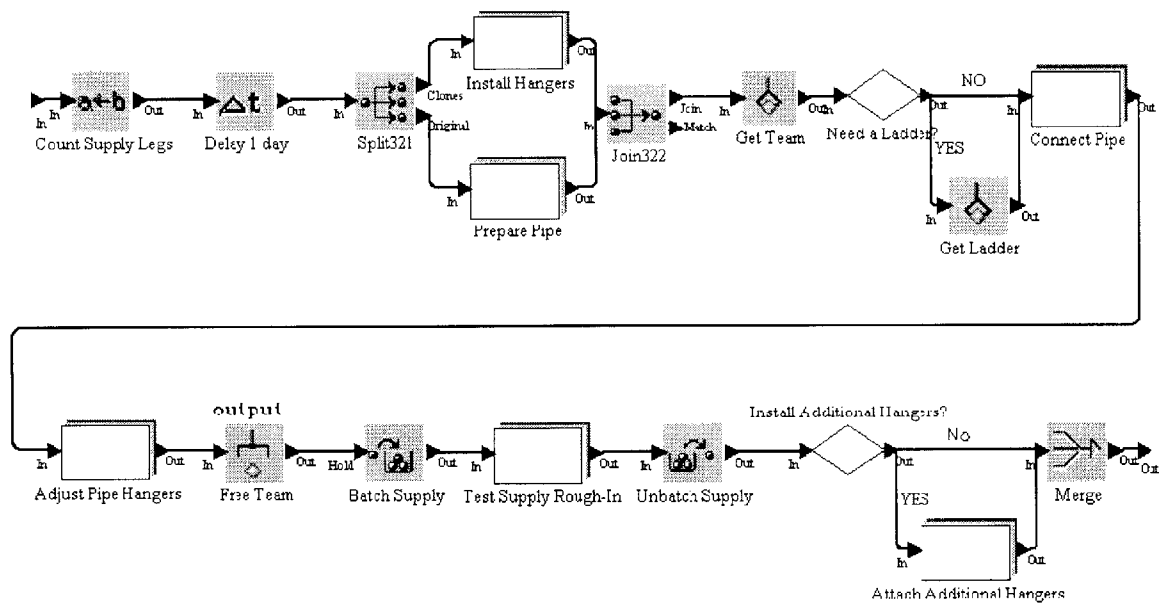


Figure 5.12: Resource Allocation for Horizontal Piping Installation

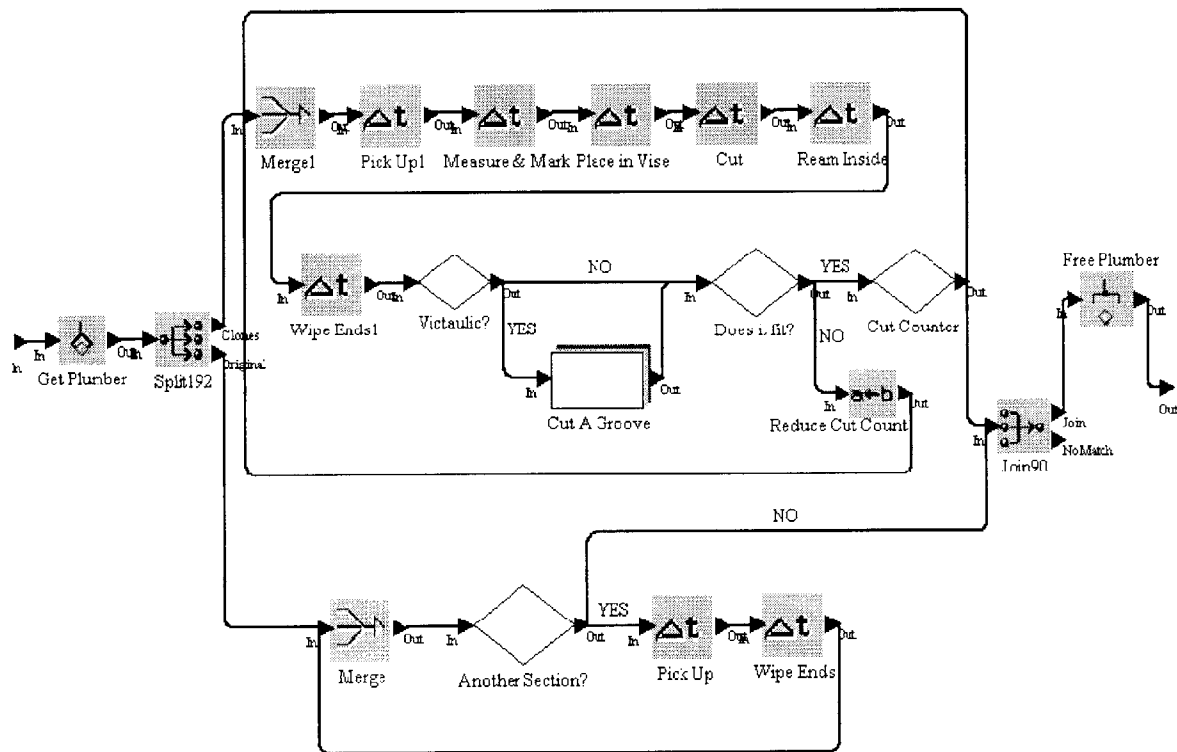


Figure 5.13: "Prepare Pipe" Process

## 5.4 Prototype Building Design

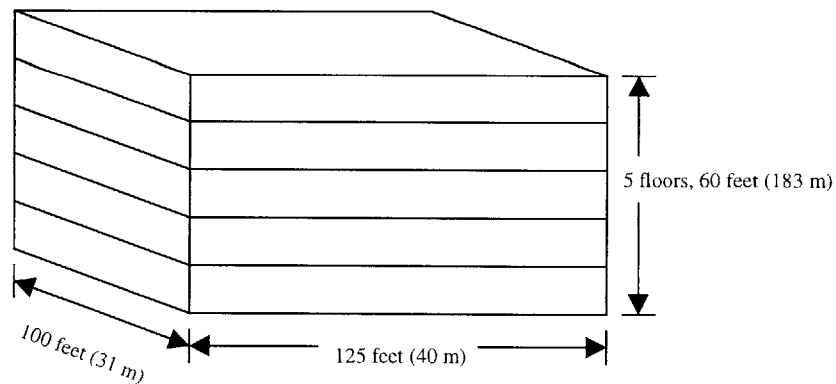
Plumbing and Fire Protection Systems were designed for a prototype building that is used to test the validity of the dynamic process models. The systems were designed to represent realistic building systems that could incorporate and test as many aspects of the model as possible.

### 5.4.1 Design Specifics

The plumbing and fire protection systems were designed based on interviews with a mechanical design firm (Craig, 1998). The interviews provided guidelines and requirements for systems in accordance with ASTM standards (ASTM, 1998). The prototype building used for previous dynamic process simulation models of concrete construction, steel erection and exterior enclosure served as the building for which the plumbing and fire protection systems were designed.

#### *Prototype Building*

The prototype building is a 5-story, rectangular building that occupies a footprint of 100 feet (30m) by 125 feet (37.9m) (Figure 5.14). Floors are supported on either steel or concrete beams, and are spaced 10 feet (3.05 m) apart. Corrugated steel decking supports the 2-inch (5 cm) concrete floor slabs. The building is enclosed by brick curtain walls, and has no sub-grade floors.



**Figure 5.14: Prototype Building Layout**

### ***Plumbing System Design***

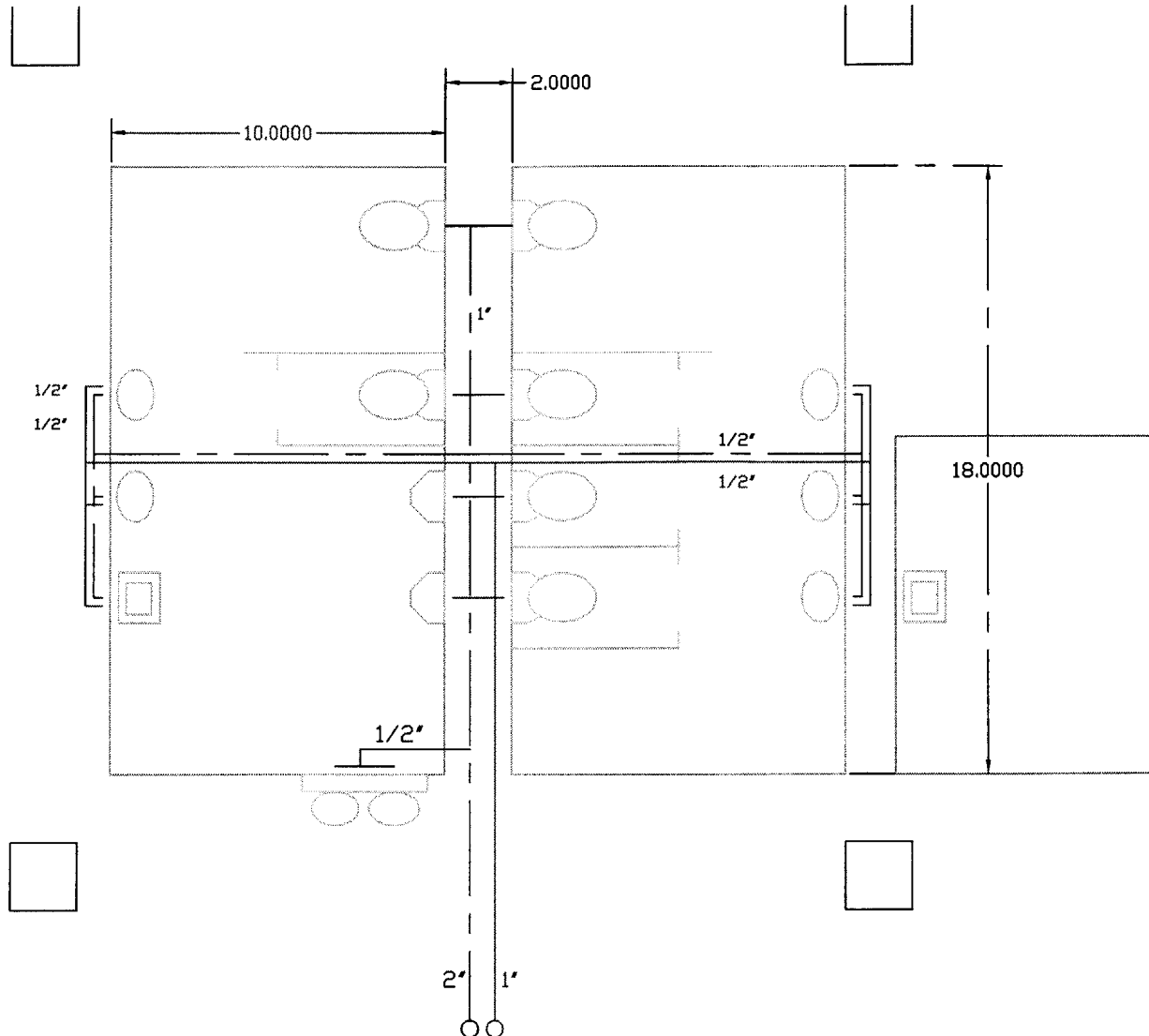
The plumbing system for the building was designed under the assumption that the building would be used as an office building, with one set of bathrooms located at the center of each floor. Figures 5.15 through 5.18 show the plumbing system details.

Supply risers and DWV stacks are located as close as possible to the fixtures to minimize horizontal runs, and the bathrooms are arranged back-to-back so that water closets for both bathrooms can share a vent and stack.

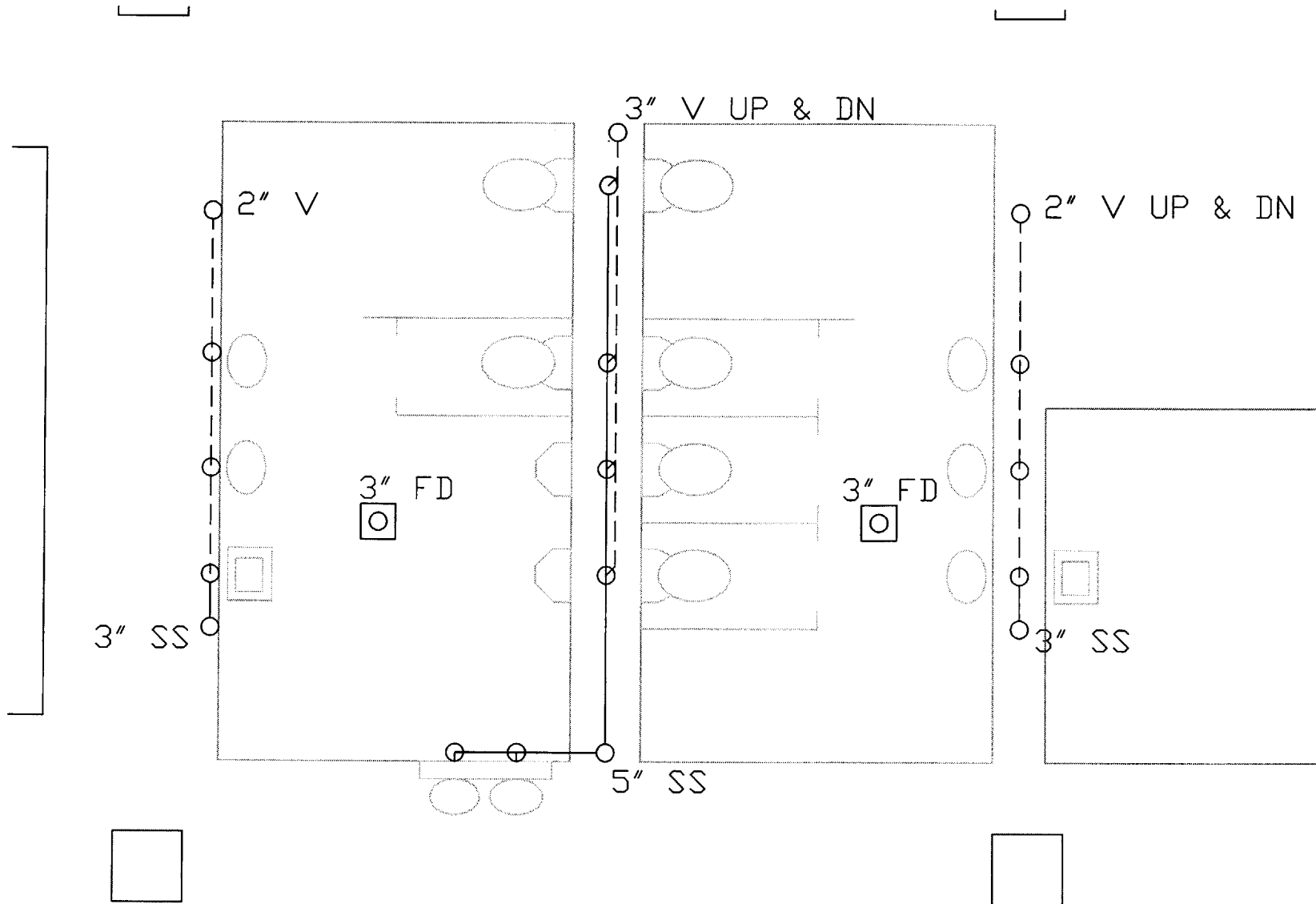
Roof drains are located near the corners of the building. They extend from the roof down to a below-grade roof drain line that runs out into the city storm sewage drain.

Below grade plumbing consists of DWV and roof drainage piping, and is tied into the city system through street sewage and storm water lines located on the western side of the building. The DWV lines are buried 3 feet (1m) below the concrete slab on grade (see Figure 5.18), and feed into the street sewage system. Roof drain lines are also buried 3 feet (1m) below the concrete slab, but they extend into a separate city storm-drainage line.

Water supply piping comes out of the ground on the outside of the building, and enters through the wall of the first floor. The plumbing system is a upfeed system, where water comes in from the street and is split into hot and cold water lines before feeding into water heaters. The hot water lines pass through the heaters and then run parallel to cold water lines to feed into bathroom fixtures on each floor. For simulation purposes, electric water heaters are located on each floor. Hot water can reach the upper floors at an adequate pressure through temperature differentials, but the cold water must be pumped at the first floor to reach the upper fixtures.



**Figure 5.15: Domestic Water Supply for a Typical Floor**



**Figure 5.16: DWV Floor Plan**

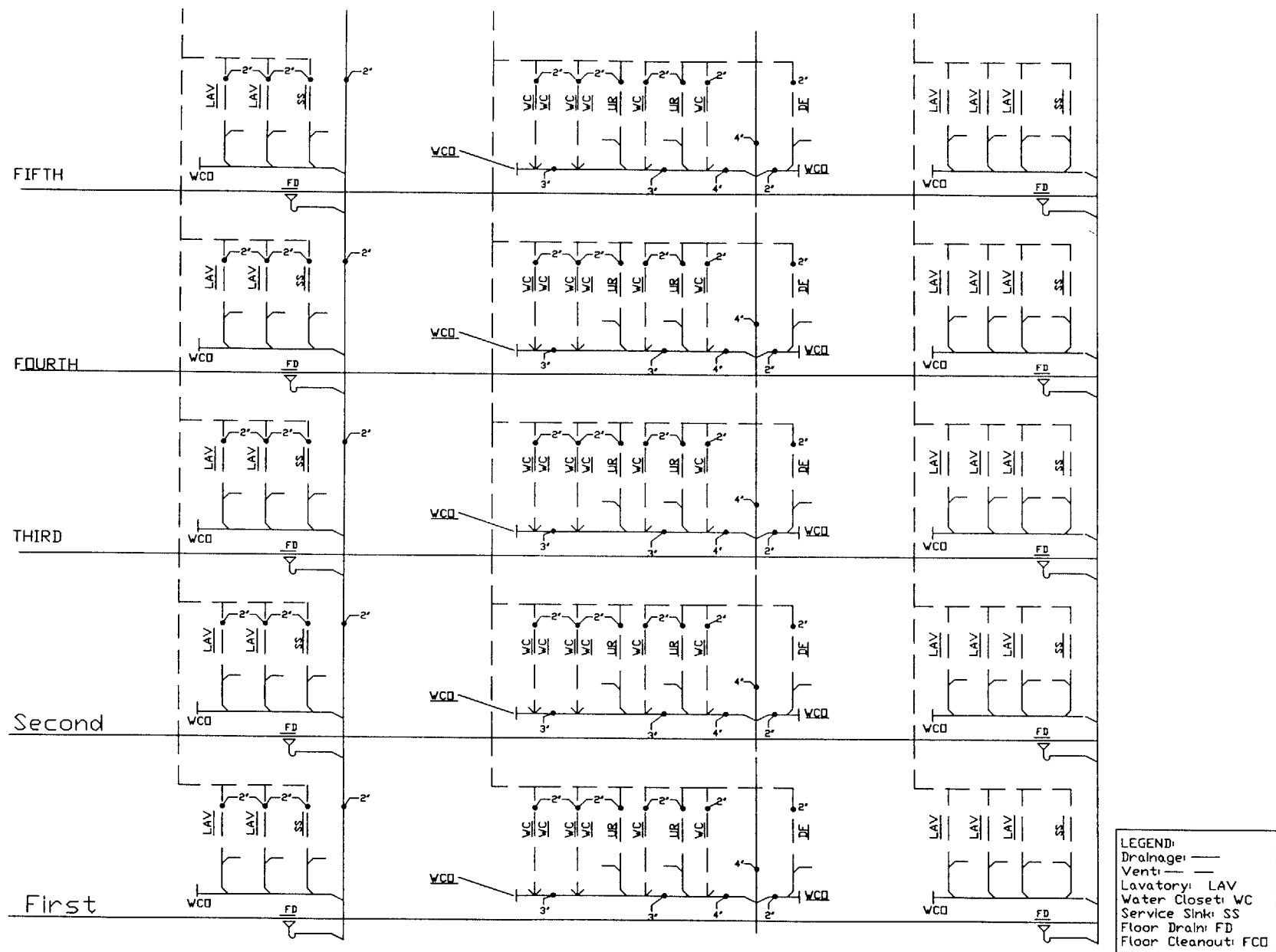
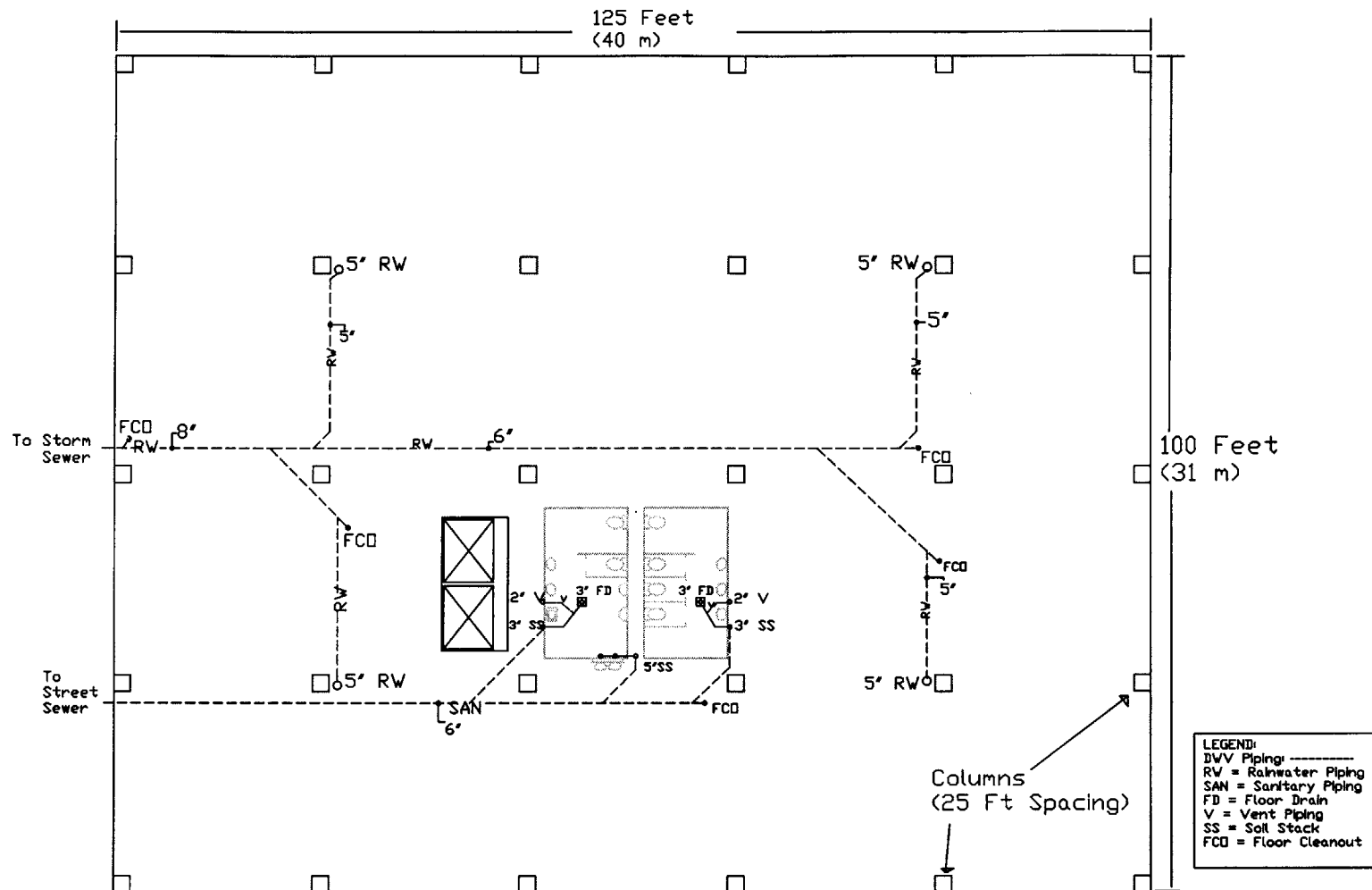


Figure 5.17: DWV Vertical Stacks Plan





**Figure 5.18: Below-Grade Plumbing**

Pipe materials and diameters used for the plumbing system were chosen to reflect realistic sizes and materials. Similarly, the fixtures used in the bathrooms represent typical fixture types found in office buildings. Table 5.4 summarizes the materials chosen for the prototype design.

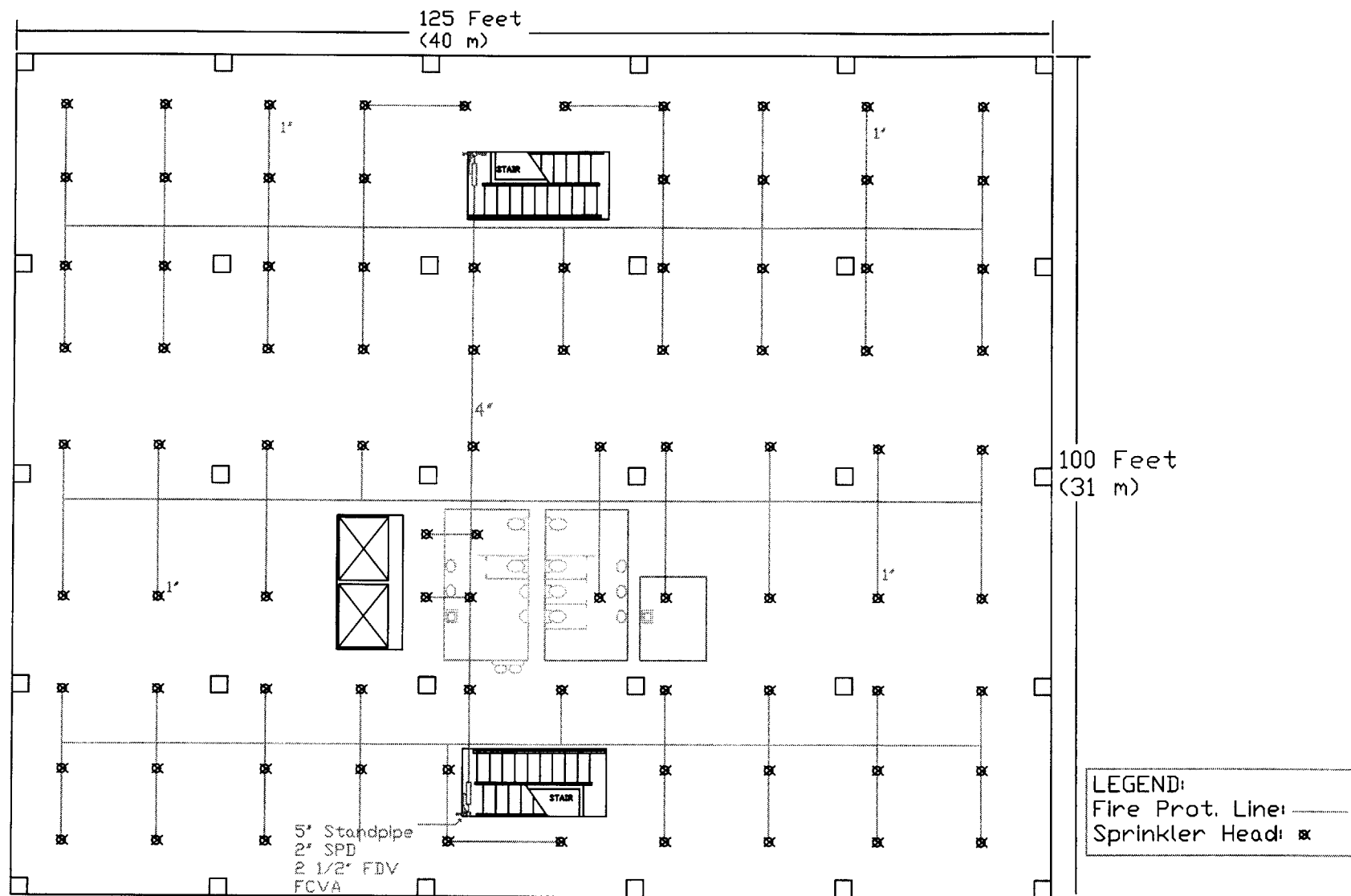
Plumbing System	Material/Type Used
Sub-Grade Piping	Cast Iron, Bell & Spigot Connections
Domestic Water Risers	Copper Piping, Soldered Connections
Domestic Water Horizontal Piping	Copper Piping, Soldered Connections
Drainage Stacks	Cast Iron, No-Hub Connections
Vent Stacks	Cast Iron, No-Hub Connections
Horizontal Drainage Piping	Cast Iron, No-Hub Connections
Water Closets	Wall-Hung, On piece with Flush-Valve
Urinals	Wall-Hung, Vitreous China
Drinking Fountain/Water Cooler	Wall-Mounted, Stainless Steel
Lavatories (Sinks)	Counter, Vitreous China, 20 inch X 22 inch (50 cm X 55 cm)
Water Heaters	Electric, 40-gallon, 17 KiloWatt
Water Supply Meter	Threaded, 1" (2.5 cm) diameter
Pumps	3 HorsePower, Pressure Booster
Fire Protection	Material/Type Used
Standpipes	Steel, Grooved Fittings
Vertical Supply Risers	Steel, Threaded Connections
Horizontal Piping	Steel, Threaded Connections
Sprinkler Heads	Pendant, Recessed , 3/8 inch (1 cm) orifice
Fire Pump	Electric, 250 Gallons Per Min, 3 inch (8 cm) Pump

**Table 5.4: Summary of Materials Chosen for Design**

### ***Fire Protection System Design***

Similar to the plumbing system design, the fire protection system was designed to meet NFPA requirements for an ordinary-hazard office building. The system is a wet-pipe system (see 4.1.2), where the horizontal pipes are constantly filled with standing water. Figure 5.19 shows the layout of fire protection piping for a building floor.

Sprinkler heads are spaced to meet the requirement of one sprinkler head per 130 square feet (14 square meters) of space. If interior walls were included in the design of the building, the sprinkler head spacing would have to be adjusted to ensure that walls did not block the heads from servicing every square foot.



**Figure 5.19: Fire Protection System for a Floor**

Each floor is serviced by a redundant system of standpipes located in each stairwell. The standpipe serves as a water supply system for the mains and branches on each floor, as well as an emergency access system for fire hoses. Unlike the plumbing system, the fire protection system has a relatively large amount of horizontal piping in comparison with the amount of vertical piping.

A fire pump is located on the first floor to provide adequate pressure in the system. Additional testing and regulating equipment is also located on the first floor with the pump.

#### **5.4.2 Construction Assumptions**

In addition to the building specifics, several assumptions had to be made about the installation process to accommodate the variety of possible installation sequences and methods that different contractors employ. Construction issues that result from overall building progress can have significant effects on the plumber's sequence of installation activities. While the model is flexible enough to handle any method of installation, a specific method is assumed for model verification purposes. The assumptions used for the prototype building are primarily based on information gathered from interviews and site visits.

##### ***Overall Building Construction Assumptions***

The computer model assumes that the prototype building is a new building, so construction begins with foundation work. Below-grade systems are installed at the earliest possible time based on the overall progress of construction for the prototype building. The slab on grade is poured after the below-grade systems have been installed and inspected. Prior to the pouring of upper floor slabs, sleeves are installed in the formwork to accommodate the penetration of risers. Rough-in of services progresses from the bottom floor to the top floor ("bottom-up"), and finish work begins after the interior walls and floors have been installed and painted.

##### ***Installation Assumptions***

For the purposes of the model, it is assumed that street utilities (water supply, sewage lines, storm drainage lines) already run to the exterior walls of the building, so exterior pipe installation is not included in the model. Trenching is required for the below-grade piping, and is performed by a backhoe operator. The simulation model assigns a "priority" attribute to below-grade entities to insure that available resources will work on below-grade plumbing before starting on the upper floors. The below grade system is not inspected until the entire system is in place, and backfill begins immediately after the inspection is complete.

Risers are installed by riser group, but they can be installed by floor if building progress constraints dictate. Sleeves are assumed to have been installed in the floor slabs prior to deck installation, so coring is not necessary for every riser. For simulation purposes, however, some coring is randomly assumed to be necessary. In areas where DWV stacks and supply risers are adjacent to each other, DWV stacks are always placed first, since the accuracy of their location is more critical (see Chapter 4).

For a particular fixture group, the DWV piping is always installed before the supply piping for the same reason that DWV stacks have priority over supply risers. In horizontal piping installation, entities are arranged so that horizontal DWV piping will be placed before supply piping if no outside constraints exist.

Hangers are installed for horizontal piping before the runs are connected, and the hangers are suspended from the corrugated steel decking for the floor above. The low floor-to-ceiling heights in the prototype building allow plumbers to use a standard stepladder to install overhead piping, so a scissors lift is not necessary.

Pipe insulation is not considered part of the plumbing installation process, because it is performed by a separate contractor and is usually performed well after the plumber has roughed-in and tested the piping.

### ***Resource Assumptions***

Production rate assumptions for crews and equipment are based on site visits, interviews, and literature. These production rates are meant to serve as general estimates. Obviously, outside factors like weather conditions, local codes, local training quality, and site conditions can have a significant impact on these rates. However, the model is flexible enough to alter the production rates for local conditions.

Costs per resource vary among different locations and companies as well. Costs assumed for this model were derived from interviews with contractors in the Boston, Massachusetts. Therefore, the costs for each crewmember are based on local 1998 wage rates for plumbers in Boston. The costs include direct labor costs and workmen's compensation costs (26% of direct labor). For heavier equipment (Backhoe), a daily fee is assumed, and is multiplied by the total number of days that the equipment is on site. Sprinkler installers are assumed to cost the same as plumbers for the Boston area. This assumption is based on the fact that many plumbing contractors perform both installation tasks. Table 5.5 lists the key resources and their associated costs for plumbing and fire protection installation. As the table shows, the total crew for both plumbing and fire protection installation consists of one foreman, four journeymen, and one apprentice. The crew remains consistent throughout the entire

project. Journeymen perform the majority of installation tasks in two-person teams, and the apprentice helps out with simple tasks as needed. The foreman performs some installation tasks, but spends the majority of his or her time supervising.

As mentioned earlier, plumbers perform the majority of their installation tasks with their own set of hand tools. However, larger equipment may be necessary for heavier or thicker sections of pipe. The model assumes that any pipe that is larger than 2 inches (5cm) in diameter must be cut from a table pipe cutter. Pipe that is smaller than 2 inches can be cut with a tube cutter, which every plumber carries. For vertical piping, stacks installation requires a hoist to lift and place the heavy pipe, but supply piping can be installed by hand. Also, large equipment or palletized loads of pipe sections are assumed to be delivered via a forklift or crane to their desired location. The model assumes that the General Contractor provides these forklifts or cranes, and that they will be available whenever the plumbing contractor needs them. In other words, for these particular installation models, resource sharing with the other building systems is ignored.

	Direct Labor (inc. Union Dues)	Workmen's Comp, etc. (26%)	O&P (29%) (inc. Tax, Ins.)	Cost per Hour	Number of Workers	Total Cost/Hour
<b>Foremen</b>	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	1	\$ 60.68
<b>Journeyman</b>	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	4	\$ 232.00
<b>Apprentice</b>	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	1	\$ 52.62
			<b>TOTAL CREW COST per HOUR</b>			<b>\$ 345.31</b>
<b>Backhoe</b>	\$ 33.11		\$ 9.60	\$ 42.71		
<b>Operator</b>	\$ 33.83		\$ 9.81	\$ 43.64		

**Table 5.5: Key Resources and Associated Costs**

## **5.5 Simulation of Plumbing Installation for the Prototype Building**

Once the process flow, project specifics, and project dynamics were incorporated into the model for the prototype building, the simulation was run. Project duration, costs, and worker exposure to dangerous conditions can be estimated based on the results of the simulation.

### **5.5.1 Duration**

The simulation model calculates the total time required for the installation of a plumbing system for the prototype building to be 288 hours, or 36 days (assuming an 8-hour workday). Table 5.6 summarizes the times required for the various sub-processes associated with plumbing installation. The table lists the overall duration as well as the installation rate for each sub-process.

The installation rates for each process are listed in terms that are familiar to plumbing contractors (Dowd, Valante, 1998) because the rates were used to verify the accuracy of the model.

	TIME	Time per Unit	Industry Estimates*
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	about 4-5 days
Test Below Grade	5 hours	4 hours	4 hours
Complete Backfill	2 days	2 days	about 2 days
Horizontal Runs:	6 days	50 LF/DAY per Crew	50 LF/Day per Crew
Risers and Stacks	11 days	1 hr/stack	1 hr/stack/team
Rough-In Fixtures	10 days	8hrs/F.G., or 2.5 hrs per Fixture	about 2.5 hrs/Fixture
Finish Roof and Floor drains	1 day	.5 hr /drains (per team)	.5 hr/drain
Finish Fixtures	6 days	2.5 hr per Fixture Group (2 teams)	2.5 hr/Fixture
Install Equipment	Varies	Varies	Varies
<b>Total Time on Site: 36 days</b>			* - based on interviews

**Table 5.6: Summary of Installation Times**

The rates are more useful than the overall installation time for each sub-process because some of the sub-processes are performed simultaneously. When crews are split among different activities, the overall time required for each activity is increased. For example, one plumbing crew installed below-grade plumbing at the same time that another crew was installing DWV stacks. If both crews had been installing DWV stacks, the overall time required to install the stacks would have been much lower than the 11 days shown in the table. The installation rate of 1 hour per stack for a two-person crew therefore serves as a better indicator of the accuracy of the model.

Figure 5.20 illustrates the progress of the installation activities over the course of the simulation. Each of the major activities (installation of below-grade plumbing, installation of equipment, rough-in and finish of fixtures, installation of vertical piping, and installation of horizontal plumbing) is represented by a separate line on the chart. Each point on a line represents the time that a particular activity was finished for an entity, so the overall time required for each sub-process can be deduced as the vertical distance between the beginning point and the endpoint on the line. For example, sub-grade plumbing installation began at time 0, and was completed at the 64-hour mark (8 days).

As Figure 5.20 shows, plumbing installation began with the installation of below-grade plumbing and DWV stacks. Following completion of the below-grade plumbing, crews began to rough in the fixtures. Once the fixtures had been roughed in, supply risers, roof drains, and floor drains were installed simultaneously. Next, horizontal plumbing was installed. Finish work began on fixtures once the associated plumbing was installed and tested, and the finish work continued until the system was complete. Equipment was installed as resources became available from other activities.

### 5.5.2 Cost

Based on the overall duration of 36 workdays, the model determines the direct labor cost associated with installation to be \$104,976 (see Table 5.7). The crew size remains constant for the entire project, so the wage rates can be multiplied by the overall duration of the project to determine total labor costs. The total direct labor cost associated with installation is multiplied by an overhead and profit (O&P) margin of 29% to account for contractor markup, insurance costs, and taxes.

	Direct Labor (inc. Union Dues)	Workmen's Comp, etc. (26%)	O&P (29%) (inc. Tax, Ins.)	Cost per Hour	Total Number of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	288	\$ 17,477
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	1152	\$ 66,817
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	288	\$ 15,155
Backhoe	\$ 33.11		\$ 9.60	\$ 42.71	64	\$ 2,734
Operator	\$ 33.83		\$ 9.81	\$ 43.64	64	\$ 2,793
<b>TOTAL DIRECT COST:</b>						<b>\$ 104,976</b>

**Table 5.7: Summary of Labor Costs for Plumbing Installation**



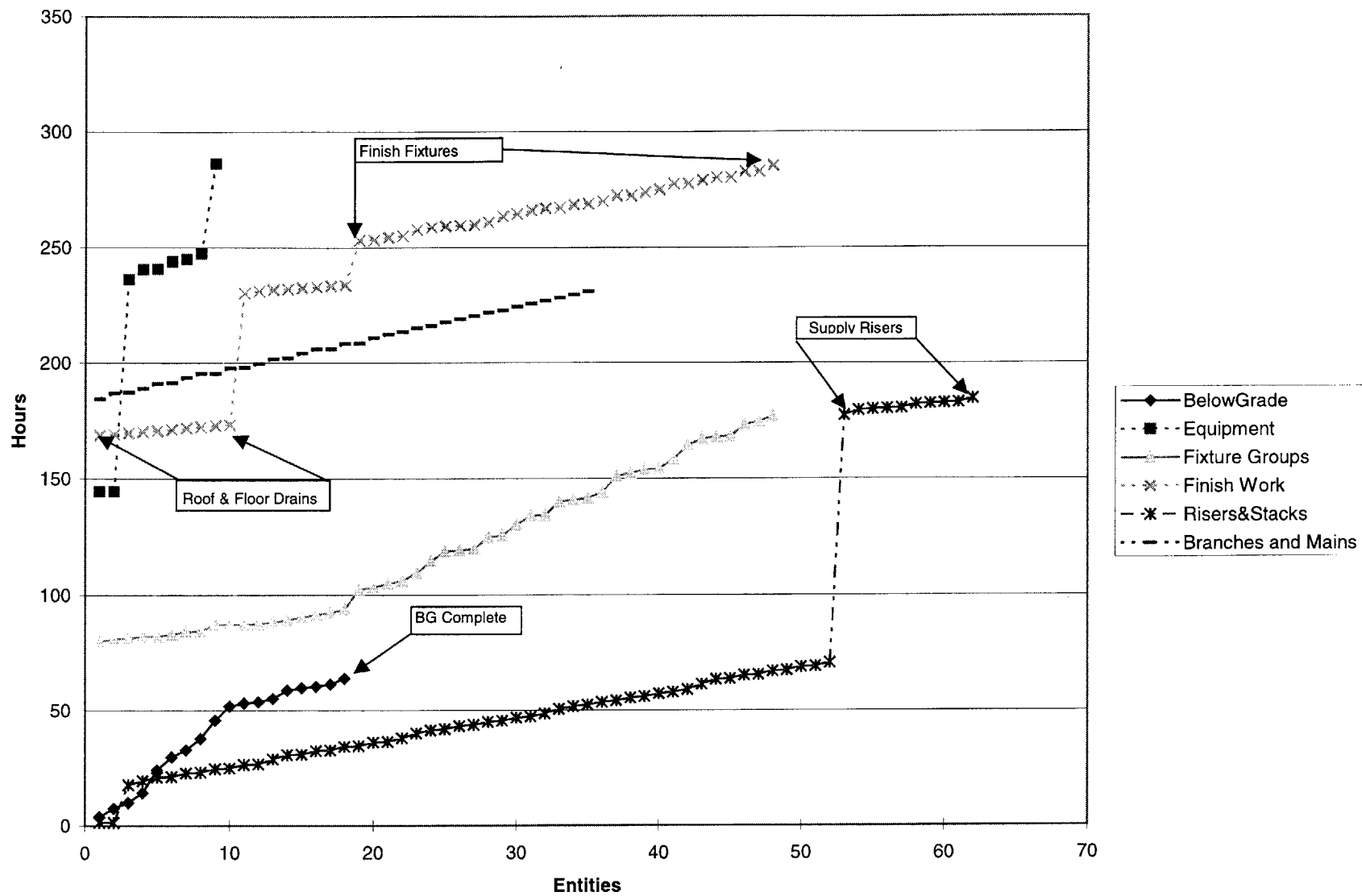


Figure 5.20: Progress of Plumbing Installation for the Prototype Building

### 5.5.3 Worker Exposure to Dangerous Conditions

Worker exposure to dangerous conditions during the installation of plumbing can be measured through a relative danger index. The danger index is based on Table 5.8, which lists the incidence rates of causes of injury in the construction industry (OSHA, 1992).

Causes of Injury in the Construction Industry	Percentage
Struck Against	8.0%
Struck By	21.0%
Caught in or Between	4.1%
Rubbed ,Abraded or Penetrated	3.5%
Fall of Person (different level)	14.9%
Fall of Person (same level)	7.0%
Bodily Reaction	31.6%
Other (Temperature, Radiation)	9.9%
<b>TOTAL:</b>	<b>100%</b>

**Table 5.8: Incidence Rates of Causes of Injury in the Construction Industry**

The danger index of a particular installation activity is the sum of all the incidence rates associated with that activity multiplied by the total time that workers spend performing the activity. The danger index for the overall plumbing installation process is the sum of all the danger indices associated with each of the activities within the process.

Table 5.9 below lists the danger indexes associated with the installation of the plumbing system for the prototype building. As the table indicates, the relative danger index is 192. This index is useful when compared with the danger indices associated with fire protection and each of the innovations tested in Chapter 6.

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment
Struck Against										8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%			
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%		4.1%
Rubbed ,Abraded or Penetrated			3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (different level)					14.9%	14.9%				
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%		
Bodily Reaction				31.6%	31.6%	31.6%		31.6%	31.6%	31.6%
Other (Temp, Rad)	9.9%	9.9%								
Incidence Rate (%)	42.0%	42.0%	7.6%	42.1%	71.0%	71.0%	35.6%	46.2%	35.1%	47.2%
Time Exposed (hrs)	56	7	20	10	120	30	60	10	48	23
Danger Index	23.52	2.94	1.52	4.21	85.2	21.3	21.36	4.62	16.848	10.856
										<b>192</b>
										<b>DANGER INDEX</b>

**Table 5.9: Danger Indexes for the Installation of Plumbing in the Prototype Building**

## 5.6 Simulation of Fire Protection Installation for the Prototype Building

### 5.6.1 Duration

The total time required for the installation of the fire protection system for the prototype building, as determined by the simulation model, is 384 hours (49 workdays). Table 5.10 summarizes the times and rates for the installation of the standpipes and risers, the horizontal piping, the equipment (alarms, pumps, etc.), and the sprinkler heads.

	TIME	Time per Unit	Industry Estimate*
Horizontal Runs	43 days	8.3 days/floor, 115 LF/day	110 LF/day
Risers and Standpipes	4 days	5 stack/day, 1.3 hr/stack/tm	1 hr/stack/team
Finish Sprinklers	5 days	66 sprinklers/day, .5 hr/spr/jnym	.5 hrs/sprinkler/jnymn
Install Equipment	Varies	Varies	Varies
<b>Total Time on Site:</b>	<b>49 days</b>		*based on interviews

**Table 5.10: Summary of Installation Times for the Fire Protection System**

As table shows, the majority of the time required to install the fire protection system is attributed to the installation of horizontal piping (43 days). This makes sense, because the fire protection system has nearly 10 times as much linear feet of horizontal piping as the plumbing system (1070 feet per floor compared with 110 feet per floor for the plumbing system). The relationship among installation activities is further illustrated in Figure 5.21, which graphically represents the various activities involved with the fire protection systems.

Fire protection installation begins with the installation of the standpipes and risers for the prototype building. Since below grade plumbing is not required for the fire protection system, though, work also begins immediately on the installation of the horizontal mains and branches. For convenience, the mains and branches are installed by floor. Once risers and standpipes are completed, the resources (journeymen) move over to help install the horizontal piping. As resources are available, equipment is installed where required. Once the horizontal piping is complete, the sprinkler heads are adjusted to fit with the interior fit out (In reality, this “finishing” process would not begin until the interior construction crew began to install ceiling tiles).

Several simulations were run to test the impacts of certain activities on the overall duration for installation. Since horizontal piping installation consumes most of the total installation time, changes that affect horizontal piping affect the overall duration the most. For example, when hanger spacing was changed from 8 feet (2.7m) to 6 feet (2m), the overall duration for installation changed from 49 days to 54

days (a 9.5% increase in overall project duration). Similar effects were found to occur for small changes in the duration of the pipe connection activities.

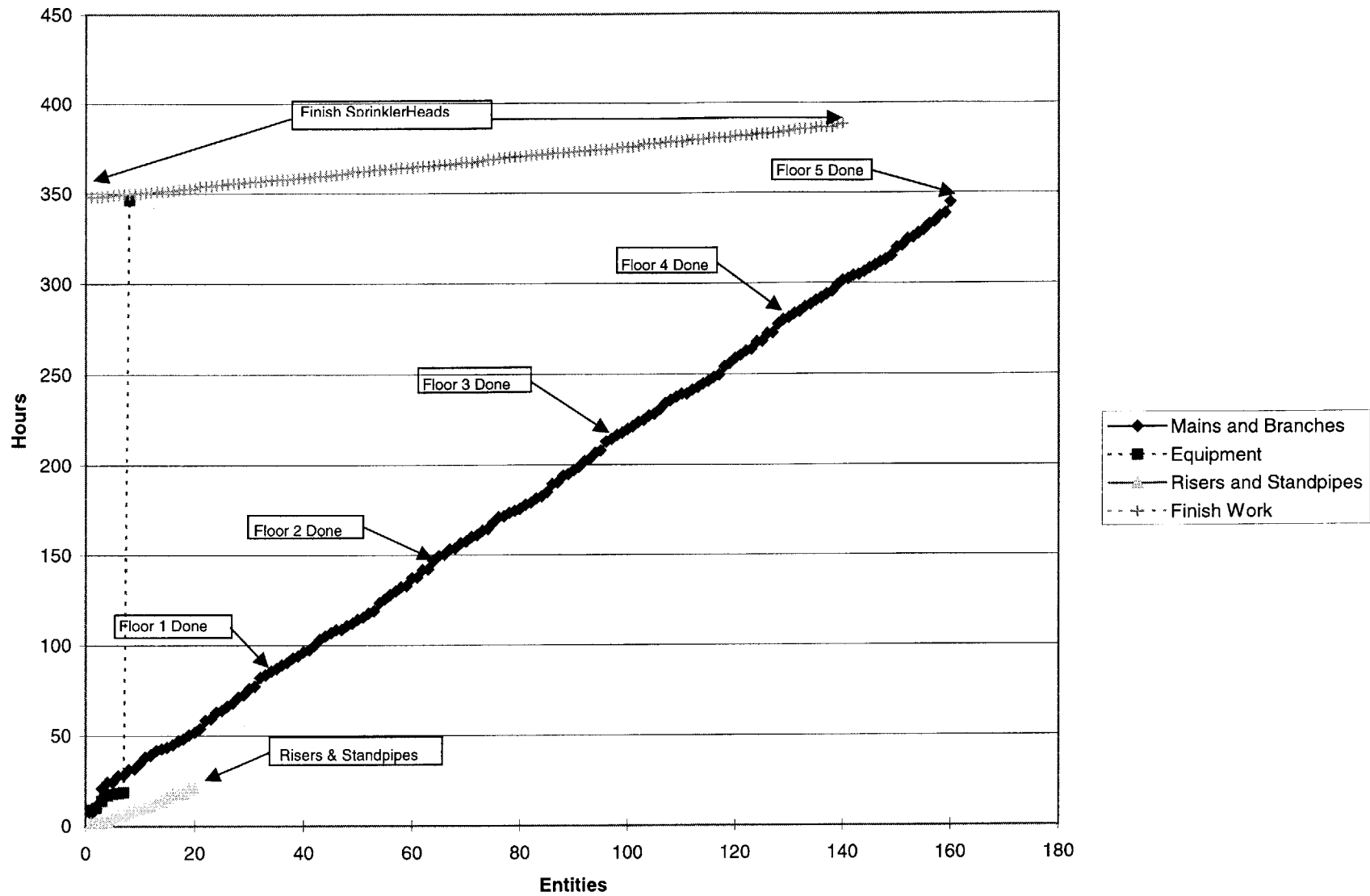


Figure 5.21: Progress of Fire Protection for the Prototype Building

### 5.6.2 Cost

Table 5.11 summarizes the labor costs associated with the installation of the fire protection system. As mentioned earlier, the costs attributed to the sprinkler installation crews are the same as those listed for the plumbing installation, because the same crews can perform either installation. As the table shows, the cost for fire protection installation, \$132,600, is substantially higher than the direct labor cost for plumbing (39% higher). The difference should be expected, since fire protection takes 15 days longer to install than plumbing for the prototype building. A backhoe is not required for the fire protection system, but the cost savings that result are not enough to offset the longer project duration.

	Direct Labor (incl. Union Dues)	Workmen's Comp, etc. (26%)	O & P (29%) (incl. Tax, Ins)	Cost per Hour	Total Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	384	\$ 23,302
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	1536	\$ 89,090
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	384	\$ 20,207
				<b>TOTAL DIRECT LABOR:</b>		<b>\$ 132,599</b>

**Table 5.11: Summary of Labor Costs for Fire Protection Installation**

### 5.6.3 Worker Exposure to Dangerous Conditions

The danger indexes associated with Fire Protection installation are listed in Appendix F. Based on these indexes, the overall danger index is 221, which is 16% higher than the danger index for plumbing (190). The danger index for fire protection is higher than that for plumbing because the sprinkler installers are exposed to the dangers associated with installing horizontal piping (falling, being struck by other pipes) for a much longer time than they are in plumbing installation.

	Prepare Pipe	Connect Pipe (Above Ground)	Install Hangers	Install Standpipes	Install Supply Risers	Finish Sprinkler Heads	Install Equipment
Struck Against							8.0%
Struck By		21.0%	21.0%	21.0%			
Caught in or Between	4.1%			4.1%	4.1%		4.1%
Rubbed ,Abraded or Penetrated	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (different level)		14.9%	14.9%			14.9%	
Fall of Person (Same level)				7.0%	7.0%	7.0%	
Bodily Reaction					31.6%	31.6%	31.6%
Other (Temp, Rad)							
Incidence Rate (%)	7.6%	39.4%	39.4%	35.6%	46.2%	57.0%	47.2%
Time Exposed (hrs)	35	350	90	15	11	40	25
<b>Danger Index</b>	<b>2.66</b>	<b>137.9</b>	<b>35.46</b>	<b>5.34</b>	<b>5.082</b>	<b>22.8</b>	<b>11.8</b>
							<b>221</b>
							<b>DANGER INDEX</b>

**Table 5.12: Danger Indexes for the Fire Protection Installation**





## **6 Analysis of Innovations**

Among professionals, common opinion is that plumbing and fire protection systems have not changed very much in the past couple of decades in terms of the materials and methods used for installation. Over twenty plumbing and fire protection contractors were interviewed for this research, and 15 could not think of a single substantial innovation that has penetrated the industry in the past twenty years. Many felt that the last major innovation in piping systems was plastic pipe (PVC), but plastic pipe was introduced back in the 1950's (Ventre, 1979).

There are some recent innovations in the industry, however, and they have the potential to significantly affect the installation process. Because they are rather new, their potential impacts have yet to be fully proven on actual projects. The simulation models developed here help to predict the impacts of the various innovations on resources, costs, installation times, as well as the dynamic relationship among installation activities.

### **6.1 Innovation #1: Flexible Piping Systems**

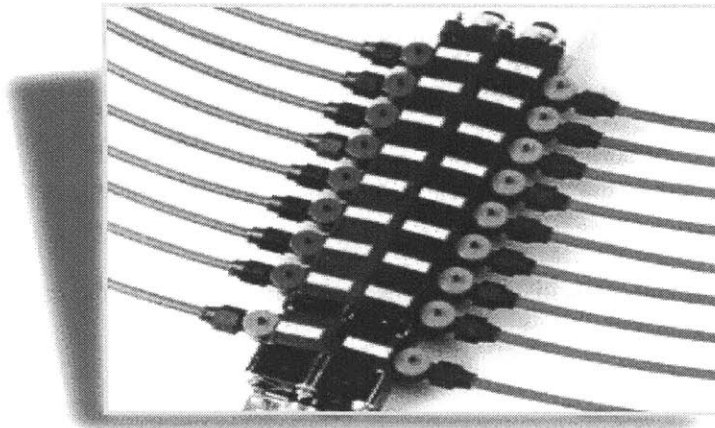
The innovations described in this Chapter affect the plumbing installation process in a variety of ways. Specifically, they can impact process flow, project specifics (in terms of design attributes, resources and production rates), or project dynamics. The innovations chosen for analyses are: 1) Flexible Piping Systems, 2) Grooved Fittings for Water Supply Systems, 3) Hot Water Re-Circulation Coils, and 4) Sovent Aerators. This chapter describes each innovation and identifies how the innovation affects the installation processes of plumbing and fire protection systems. A simulation is run for each innovation for the relevant system, and summaries of the innovation's effects on cost, safety, and installation duration are discussed.

#### **6.1.1 Description**

Flexible pipe systems consist of cross-linked polyethylene pipes that are flexible enough to “snake” around bends and turns in a run, and strong enough to convey water at standard temperatures and pressures (Vanguard, 1997). When used in combination with a manifold distribution system, they serve as an alternative to traditional two-pipe water supply systems like the one described in the prototype model.

In flexible pipe systems, each plumbing fixture in a building is served by a dedicated water line from a central manifold plumbing control unit (Figure 6.1) that acts like a “breaker box” for hot and cold water lines. The breaker boxes, centrally located on every other floor in a building, have a separate hot and cold water line for each fixture. Separate lines help to reduce water consumption, because they allow

hot water to reach a fixture by as much as three times faster than traditional systems (Cantrell, 1998). Current designs and building codes only permit the use of flexible pipe for low pressures, so the flexible pipe systems can only be used for buildings that are 5 floors or less. Plumbing unions in California are beginning to incorporate flexible pipe installation into their training plans though, and have found that the installation process is relatively simple (Cantrell, 1997).



**Figure 6.1: Flexible Pipe System Manifold**

The centralized distribution of water supply in the flexible pipe system allows plumbers to repair the system more easily as well. Should a particular fixture have a problem, the repair person can go to the manifold unit, find the dedicated water line for that particular fixture, and shut the line off without affecting the rest of the plumbing system.

Flexible pipes can be installed more quickly and with fewer fittings since an elbow connection is not required every time the pipe branch has to turn. The pipe material is also much easier to transport because it is stored in 100 foot spools instead of 20 foot sections, and the pipe itself weighs less than traditional copper or steel pipe sections.

Flexible pipe systems may also have a positive effect on outside building systems like HVAC, because they are less obtrusive than rigid pipe systems. As a result, plumbing contractors will not have to spend as much time coordinating with the other system contractors in confined areas.

### **6.1.2 Modeling Implications**

#### ***Changes in the Process Flow***

The incorporation of a flexible pipe system does not have a significant effect on the overall process flow for plumbing installation, but it does alter the steps required for installation of supply risers, horizontal supply runs, and water supply rough-in for fixtures.

Additional installation activities are required for the installation of the manifold distribution boxes on the each floor. Copper supply risers will feed the manifolds, so an additional step is required in the installation of supply risers to account for the manifold.

Water supply rough-in will be simplified by flexible pipes, because the plumber will no longer have to “snake” through a complicated series of wall studs and DWV piping in a confined space. In fact, the water supply rough-in process includes the horizontal supply runs, since the runs begin at the manifold and terminate at the fixture. Therefore, the installation of horizontal supply runs can be ignored as a separate process.

### ***Changes in Project Specifics***

#### **Design Attributes:**

The flexible pipe system affects the water supply system design in the same ways that the system affected the process flow. Specifically, the design characteristics and locations of the supply risers, horizontal runs, and supply rough-in change for a flexible pipe system. Other plumbing systems, like fixtures and the DWV system are not affected by the innovation.

The manifold distribution box should be located as close to the fixture groups as possible, so the supply risers will need to be moved closer to the bathroom systems if possible. Tee connections are no longer necessary at each floor, though, since flexible lines have replaced horizontal supply runs.

Connections are no longer necessary at intervals equal to the length of a pipe section, because flexible pipelines can span as much as 100 feet (32 m) continuously. Additional hangers will be necessary, however, because hangers are required every 32 inches (81cm) on a flexible pipe run. The reduction in connections and increase in hangers is reflected in the model’s data chart (see Appendix A), where two additional columns were added for the flexible plumbing simulation. Specifically, columns were added in the fixture group data table for the length of the flexible supply run, and for the hanger spacing requirement of 32 inches.

#### **Resources:**

Flexible pipe runs only require one plumber to install, except when the hangers are installed to support the pipe. Even during the supply rough-in of fixtures, only one plumber is needed to place the flexible pipe. Plumbers can cut the pipe with hand tools, and connections are made manually with a set of crimpers. According to Vanguard, installation of the manifolds requires one plumber, and takes approximately three hours per installation (Cantrell, 1996).

Additional heavy equipment is not needed to transport the pipe materials, because the pipe is lightweight and can be rolled like a wheel.

***Production Rates:***

Vanguard, the leading manufacturer and distributor of flexible pipe systems, claims that plumbers have reported as much as a 50% reduction in installation times for water supply systems (Vanguard, 1996). Plumbers also report that they can install a flexible pipe run at a rate of approximately 100 linear feet (32m) per day, compared with the 50 linear feet (16m) per day rate associated with copper pipe installation (Cantrell, 1996).

Connections are still necessary in tight-turn areas for flexible pipe, and where flexible pipe meets fixture units. The connections are made with a metallic couple that is crimped over each end, and according to the manufacturer's literature, require approximately 10 minutes per connection (Vanguard, 1996).

Additional hangers are necessary for flexible pipe, but they are smaller and easier to install than the Clevis hangers used for rigid pipe. Each flexible pipe hanger is similar to a clamp-style hanger, and is estimated to require 8 minutes to install (R.S. Means, 1998).

***Changes in Project Dynamics***

As mentioned earlier, flexible pipes may have a positive effect on the overall progress of the building, because they reduce the coordination time required between conflicting services like HVAC and electrical systems. However, they do not impose any logical constraints on the overall building, so progress of the overall building does not have to change as a result of the flexible pipe system.

The only additional technical constraint imposed on the flexible pipe system is the requirement for additional hangers to stabilize the flexible pipe runs. As mentioned earlier, the hanger spacing required for flexible piping is 32 inches (81 cm).

The flexible pipe system does not require specialized labor or equipment, so it does not bring about any additional resource constraints to the model. As mentioned earlier, Plumbing Trade Unions in California have begun to include training in flexible pipe installation, and have found that the process is quite simple to learn (Cantrell, 1998). They also like the system because it does not require the use of open flames, and is consequently a safer method than traditional soldered connections.

Activity	Implication
<b>Horizontal Piping Installation</b>	Supply piping not included as horizontal piping for flexible piping.
<b>Fixture Group Rough-In</b>	Supply rough-in includes all piping from the manifold to the fixture.
<b>Equipment Installation</b>	Manifolds must be installed on each floor, near the room system.
<b>Model Attributes</b>	Attributes of "Flexible Supply Pipe Length," and "Hanger Spacing" added to attribute data.

**Table 6.1: Summary of Flexible Pipe Modeling Implications**

### 6.1.3 Results for Flexible Piping Simulation

The overall duration for the installation of the prototype building's plumbing system, using flexible water supply piping, is 224 hours (28 days). The 28-day duration represents a 22% reduction in installation time from the installation of the traditional copper-based plumbing system. The most significant changes occurred in the installation of horizontal supply piping and the rough-in of the fixtures. As shown in Table 6.2, the installation time required for horizontal piping was effectively reduced to zero, since the flexible pipes were considered part of the fixture rough-in process. Conversely, the rough-in rate for fixtures increased 75% to a rate of 4 hours per fixture, since the supply rough-in included all of the flexible piping that went from the manifold to the fixture. As a result, the total duration for fixture rough-in increased from 10 to 14 days.

	TIME	Time per Unit for Flexible Piping	Original Time
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	4 ft/hr
Test Below Grade	5 hours	4 hours	4 hours
Complete Backfill	2 days	2 days	2 days
<b>Horizontal Runs:</b>	<b>0 days</b>	<b>Replaced by direct lines to fixtures</b>	<b>50 LF/DAY per Crew</b>
Risers and Stacks	12 days	1 hr/stack	1 hr/stack
<b>Rough-In Fixtures</b>	<b>14 days</b>	<b>12 hrs/F.G., or 4 hrs per Fixture</b>	<b>8hrs/F.G., or 2.5 hrs per Fixture</b>
Finish Roof and Floor drains	1 day	.5 hr /drains (per team)	.5 hr /drains (per team)
Finish Fixtures	6 days	2.5 hr per Fixture Group (2 teams)	2.5 hr per Fixture Group (2 teams)
Install Equipment	Varies	Varies	Varies
<b>Total Time on Site:</b>		<b>28 days</b>	

**Table 6.2: Summary of Duration by Sub-Process for Flexible Piping**

The overall relationships among the various plumbing installation sub-processes changed slightly as a result of the incorporation flexible piping. As discussed earlier, the most significant change occurred in the installation of horizontal mains and branches. The horizontal piping associated with the fixtures was included in the fixture groups, so the horizontal installation process is not reflected in Figure 6.2

below. As a result, fixtures were installed (finished) as soon as rough-in was complete. The manifolds on each floor needed to be installed before the fixture groups, so the “equipment” branch below begins much earlier in the overall installation process than it did for the original plumbing simulation.

The 5-day savings in overall installation time for the plumbing system results in a total direct labor cost reduction of \$21,400 (20 %). Appendix F contains complete cost calculations for each innovation.

The reduced exposure to the dangers associated with connecting pipes above ground results in a 34% reduction in the overall danger index to a value of 135 (see Appendix E). Plumbers are not exposed to the dangers of working with the open flames required for soldered connections, and they only have to connect pipe at the manifold and at the fixture itself. Additional time is required to install hangers, but the hangers only require a small drill and are relatively safe to install. Table 6.3 summarizes the differences in duration, cost, and safety between the flexible pipe system and the baseline plumbing system simulated in Chapter 5.

	Flexible Pipe	Baseline	% Change
Duration	28 days	36 days	-22%
Cost	\$ 83,580	\$ 104,976	-20%
Danger Index	135	192	-34%

**Table 6.3: Comparison Between the Flexible Pipe and Baseline Plumbing Systems**

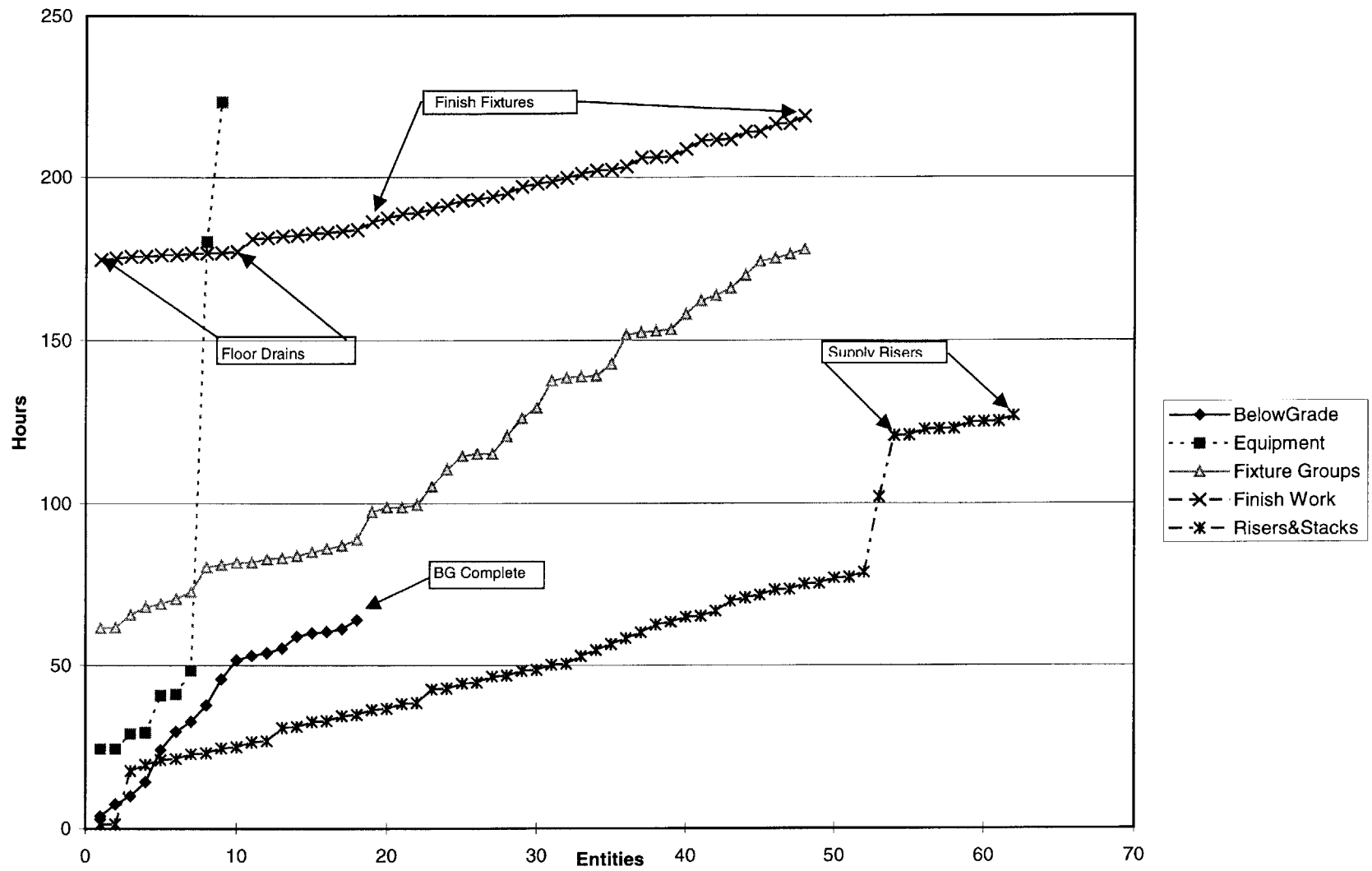


Figure 6.2: Progress of Plumbing Installation with Flexible Piping

## 6.2 Innovation #2: Grooved Fittings for Water Supply

### 6.2.1 Description

A grooved fitting, often mistakenly referred to as a “Victaulic” fitting (Victaulic is the name of the original developer of the fittings), is a mechanical coupling method for rigidly connecting copper pipe. According to Grinnell®, a leading manufacturer of grooved fittings, the fittings require less time and equipment to connect pipe sections than traditional welded or epoxy connections require (Grinnell, 1997). Figure 6.3 illustrates how the grooved fitting works.

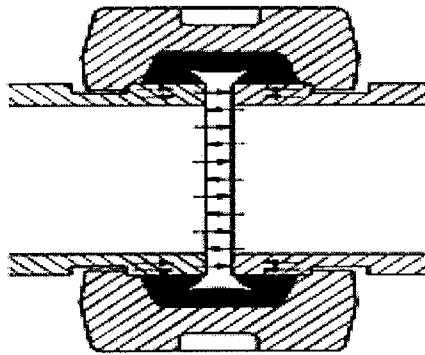


Figure 6.3: Grooved Fitting (Grinnell, 1997)

The grooved fitting uses a mechanical coupling ring to connect two segments of pipe. The mechanical coupling ring consists of a rubber gasket that slides over each end of pipe and a metal housing holds the gasket in place. Preliminary tests performed by Grinnell indicate that the fittings are less likely to leak than soldered connections (Grinnell, 1996). The fittings are also easier to disassemble during repairs, since they are not physically adhered to the pipe sections like soldered connections.

A different mechanical coupling ring is required for every different size of piping. In other words, a 3 inch (7.6cm) coupling piece could not be used to connect 2 inch (5 cm) segments of pipe. Plumbers must therefore order the proper coupling sizes for each different pipe diameter.

### 6.2.2 Modeling Implications

#### *Changes in the Process Flow*

The use of grooved fittings for water supply systems does not affect the overall process flow for plumbing installation, but it does affect the process steps for preparing and connecting pipes.



## ***Changes in the Process Flow***

The use of grooved fittings for water supply systems does not affect the overall process flow for plumbing installation, but it does affect the process steps for preparing and connecting pipes.

Pipe sections for grooved systems can be bought with grooves already cut into each end. When a section is cut, a new groove must be cut into the section. In order to reflect this additional activity in the model, two additional steps are required in the “Prepare Pipe” process. After cutting a pipe section to a specified length, plumbers must then place the pipe section in the roll-grooving machine and cut a groove into the section.

The “Connect Pipe” process for grooved fittings is very different from the traditional soldering process for copper supply pipes. The grooved connection process is summarized in Figure 6.4 below. As the diagram shows, the plumber checks the gasket, slides it over the ends of each pipe section, places the housing over the gasket, and then tightens the housing.

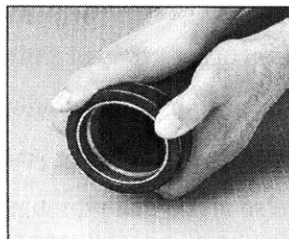
### **1. Check & lubricate gasket**

Check the gasket to be sure it is compatible for the intended service. Apply a thin coating of Gruvlok lubricant to the outside and sealing lips of the gasket. Be careful that foreign particles do not adhere to lubricated surfaces.



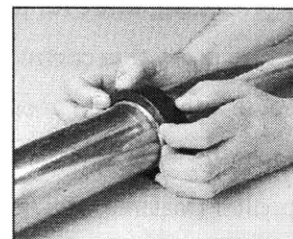
### **2. Gasket Installation**

Slip the gasket over one tube end making sure the gasket lip does not overhang the tube end.



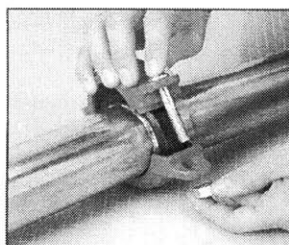
### **3. Alignment**

After aligning the two tube ends together, pull the gasket into position centering it between the grooves on each tube. The gasket should not extend into the groove on either tube.



### **4. Housing**

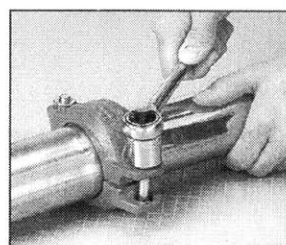
Remove one nut and bolt and loosen the other nut. Place one housing over the gasket making sure the housing keys fit into the tube grooves. Swing the other housing over the gasket and into the grooves on both tubes making sure the tongue and recess of each housing are properly mated.



### **5. Tighten Nuts**

Re-insert the bolt and run-up both nuts finger tight. Securely tighten nuts alternately and equally until fully tightened keeping the gaps at the bolt pads evenly spaced.

CAUTION: Uneven tightening may cause the gasket to pinch. Gasket should not be visible between segments after bolts are tightened.



### ***Changes in Project Specifics***

#### **Design Attributes:**

The design specifics of the plumbing system do not have to change to accommodate the grooved fittings. The water supply system can still be placed in the same locations, and pipe diameters can remain the same.

#### ***Resources:***

The only additional resource required for the grooved fittings is the roll-grooving machine itself. Since the machine is required to prepare any cut section of pipe, a bottleneck may occur at the roll-grooving machine if there aren't enough machines available. Similar to a table-sized pipe cutter, the roll-grooving machine takes approximately two minutes (based on site observations) to cut a groove into the pipe after the plumber places the pipe on the machine. For simulation purposes, two machines are assumed to be on site.

Plumbers do not need any special tools to connect pipe with grooved fittings. The only tool required is a standard wrench to tighten the coupling ring.

#### ***Changes in Production Rates:***

The production rates of particular resources are not affected by the grooving system, although the activity processing times for preparation and connection of the pipe change significantly.

Fire protection contractors have been using grooved fittings for several years, and are quite confident that the simpler connection results in shorter installation times. Many plumbing contractors believe that the labor savings are not as apparent in plumbing systems, though, because pipe diameters are much smaller (Valante, 1997). Plumbers also argue that plumbing supply runs typically have many more bends and turns than fire protection runs, and that the grooved fitting would be too cumbersome on tight turns.

Interviews with experienced fire protection contractors from around the country (Dowd, Valante, 1997) indicate that pipe preparation times for a particular run of pipe increase by approximately five minutes for each run of pipe, since the cut sections have to be grooved. However, each pipe connection takes approximately five minutes, as opposed to the typical 10 minutes required for a soldered connection.

#### ***Changes in Project Dynamics***

Grooved fittings do not impose any logical, technical, or resource-allocation constraints on the dynamics of the installation process. The fittings do not impact the overall progress of the building, and

### *Changes in Project Dynamics*

Grooved fittings do not impose any logical, technical, or resource-allocation constraints on the dynamics of the installation process. The fittings do not impact the overall progress of the building, and adjacent systems (electrical, HVAC) are not affected. Plumbers do not need any specialized training or equipment to install the connections, so resource allocation will not be impacted by the change in fittings.

The mechanical fittings are safer to install than traditional soldered connections, because they do not require the use of a torch or any special chemicals.

### **6.2.3 Results**

As mentioned earlier, the use of grooved fittings significantly affects the “prepare pipe” and “connect pipe” processes. For this reason, the effects of the innovation are most apparent in the activities that involve pipe installation. Simulations were run to assess the grooved fittings’ impacts on both the plumbing and fire protection systems.

#### **6.2.3.1 Plumbing Results**

The overall duration for the installation of the prototype building’s plumbing system, using grooved fittings is 250 hours (32 days). This represents an 11% reduction in total installation time from the plumbing system tested in Chapter 5. The most significant changes occurred in the installation of horizontal supply piping (see Table 6.4). The use of grooved fittings instead of soldered fittings significantly changed the rate at which the supply piping was connected, resulting in a 3-day reduction in horizontal piping installation duration. Plumbers were able to install horizontal piping at a rate of 90 linear feet (29 m) per day, compared with the 50 linear feet (16 m) per day rate for soldered connections.

	TIME	Time per Unit	Original Time
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	4 ft/hr
Complete Backfill	2 days	2 days	2 days
<b>Horizontal Runs:</b>	<b>3.5 days</b>	<b>90 LF/day/crew</b>	<b>50 LF/DAY per Crew</b>
Risers and Stacks	11 days	1 hr/stack	1 hr/stack
Rough-In Fixtures	8 days	8hrs/F.G., or 2.5 hrs per Fixture	8hrs/F.G., or 2.5 hrs per Fixture
Finish Roof and Floor drains	1 day	.5 hr /drains (per team)	.5 hr /drains (per team)
Finish Fixtures	6 days	2.5 hr per Fixture Group (2 teams)	2.5 hr per Fixture Group (2 teams)
<b>Total Time on Site:</b>	<b>32 days</b>		

**Table 6.4: Summary of Duration by Sub-Process for Grooved Fittings**

The 4 day savings in overall installation time for plumbing results in a total direct labor cost of \$91,860, which is \$13,100 (12.5%) less than the cost associated with soldered connections (see Appendix F).

The danger index for the plumbing system is reduced by 29% to a value of 136 when the grooved fittings are used instead of soldered connections. The significant reduction is a result of the reduced worker exposure to open flames during connection. Table 6.5 summarizes the differences between the plumbing system simulated in Chapter 5 and a plumbing system that uses grooved fittings.

	Grooved Fittings	Baseline	% Change
Duration	32 days	36 days	-11%
Cost	\$ 91,860	\$ 104,976	-13%
Danger Index	138	192	-29%

**Table 6.5: Comparison Between Grooved Fittings System and Baseline System**

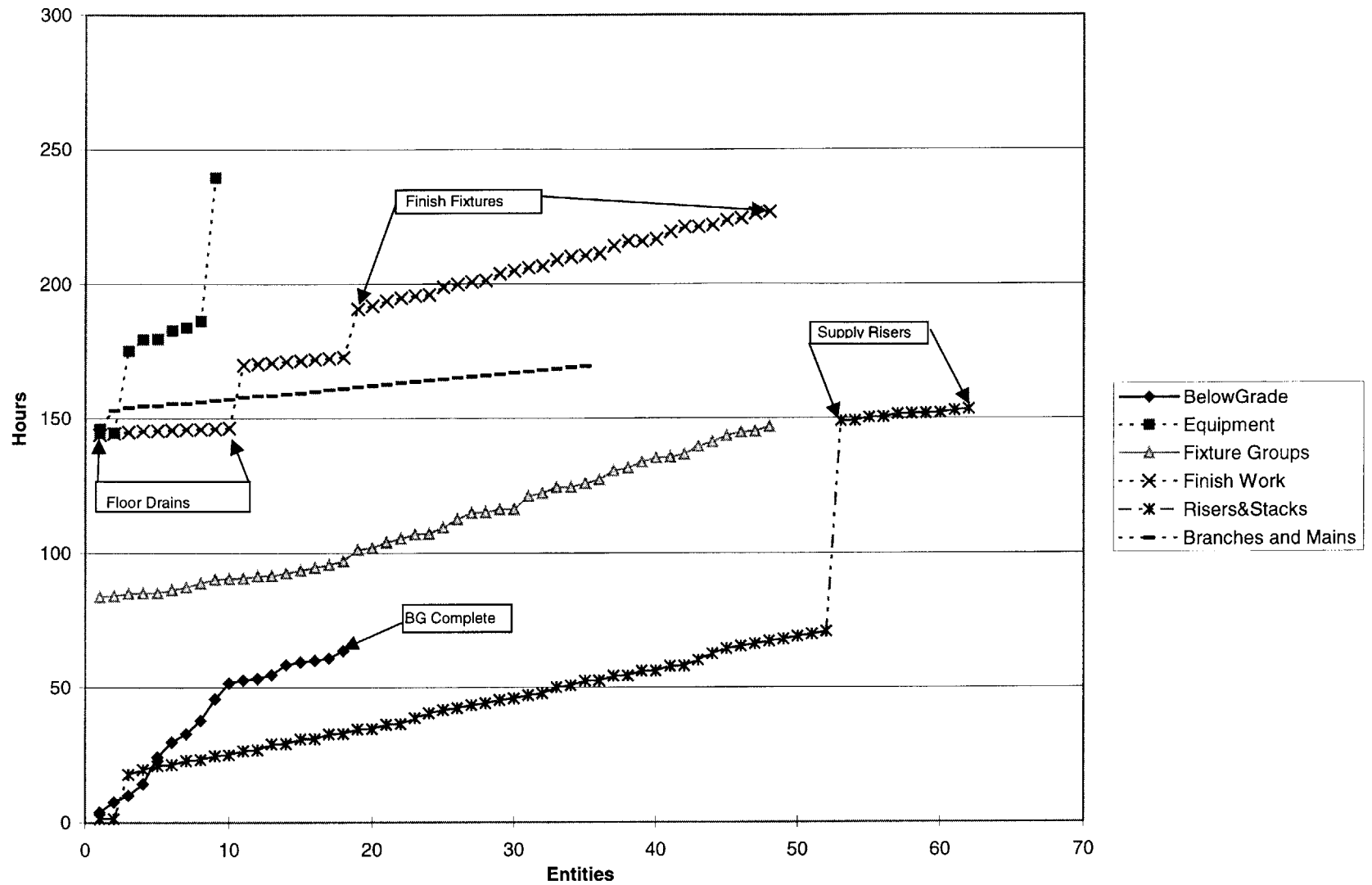


Figure 6.5: Progress of Plumbing Installation for Grooved Fittings

### 6.2.3.2 Fire Protection Results

The original fire protection system simulated in Chapter Five included grooved fittings for the vertical risers and the mains, so the impacts of the grooved fittings only pertain to the branches of the fire protection system, which were originally threaded connections. To investigate the total impact that the grooved fittings can have when used instead of threaded fittings, two simulations were conducted in addition to the original simulation in Chapter Five. In the first simulation, the entire fire protection system, including risers and mains, used threaded connections. In the second simulation, the entire system of piping used grooved fittings. The results of the three simulations are summarized in Table 6.6 below.

	Threaded Connections		Grooved Connections		Original Time	
	TIME (days)	Time per Unit	TIME (days)	Time per Unit	TIME (days)	Time per Unit
Horizontal Runs	48	8.8 day/fir, 100 LF/day	40	8 day/fir, 130 LF/day	43	8.3 day/fir, 115 LF/day
Risers and Standpipes	4	4 stack/day, 2 hr/stack/trm	3.5	5 stack/day, 1.3 hr/stack/trm	4	5 stack/day, 1.3 hr/stack/trm
Finish Sprinklers	5	66 spr/day, .5 hr/spr/jnym	5	66 spr/day, .5 hr/spr/jnym	5	66 spr/day, .5 hr/spr/jnym
Install Equipment	-	Varies	-	Varies	-	Varies
<b>Total Time on Site:</b>	<b>53</b>		<b>46</b>		<b>48</b>	

**Table 6.6: Comparison of Fire Protection Installation for Grooved or Threaded Fittings**

The overall duration for the installation of the fire protection system for the prototype building, using grooved fittings for all fire protection piping is 370 hours (46 days). As expected, the most significant changes that resulted from the innovation occurred in the installation of horizontal piping (see Table 6.6). The use of grooved fittings instead of threaded fittings for the branches resulted in an overall time savings of 20 hours (4 hours per floor) from the original fire protection system tested in Chapter 5. Sprinkler installers were able to install horizontal piping at a rate of 130 linear feet (41 m) per day, compared with the 100 linear feet (37 m) per day rate associated with threaded piping.

Figure 6.6 shows the progress of the various installation sub-processes associated with fire protection installation using all grooved fittings. As the figure shows, the relationships among the sub-processes (installation of risers and standpipes, installation of equipment, etc.) did not change as a result of the grooved fittings, but the slope of the “horizontal piping” decreased slightly from the simulation in Chapter 5. As with the plumbing installation, the decrease in slope is a result of the faster installation rate for the new fittings.

The use of a combination of grooved fittings for the risers and threaded fittings for the horizontal mains and branches led to a total direct labor installation cost of \$127,000. Compared with the prototype system, the all-grooved connection system saved \$5,600 (4.2%) as a result of the overall time reduction of

2 days. Compared with a threaded fitting system, the grooved fittings saved 13% by reducing the overall installation process by 7 days.

The 2-day savings in installation time also lowered the danger index associated with installation to 210. Compared with the prototype building (danger index of 221), this means a reduction of 5 %. The reduction was primarily the result of the reduced exposure time associated with the installation of horizontal piping at heights above 6 feet (2 m). The threaded system yielded a danger index of 232. Compared with the threaded system, the grooved system reduced the danger index by 10%. Table 6.7 summarizes the differences in cost, duration, and safety among the threaded system, the baseline model, and the grooved fitting-based fire protection systems.

	All Threaded Connections	Threaded Risers & Grooved Branches (Baseline System)	All Grooved Connections	% Change from Baseline System to All Grooved	% Change from All Threaded to All Grooved
Duration	53 days	48 days	<b>46 days</b>	-4.3%	-13.2%
Cost	\$ 146,410	\$ 132,600	<b>\$ 127,000</b>	-4.2%	-13.1%
Danger Index	232	221	<b>210</b>	-4.9%	-9.5%

**Table 6.7: Comparison Between Threaded and Grooved Fittings for Fire Protection**

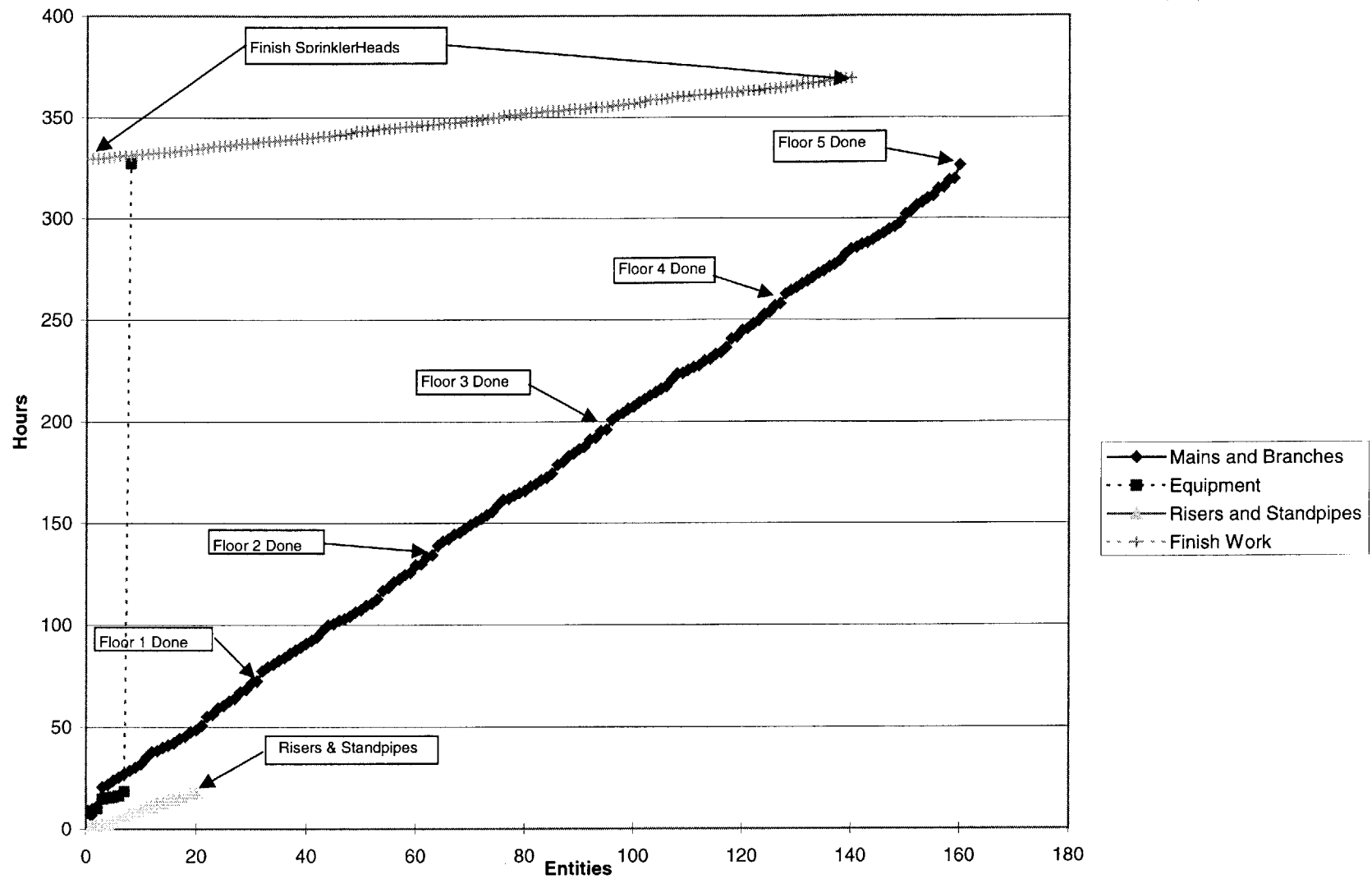


Figure 6.6: Progress of Fire Protection Installation with Grooved Fittings



## 6.3 Innovation #3: Hot-Water Re-Circulation Coils (Gravity Film Exchange System)

### 6.3.1 Description

Vaughn Manufacturing® has developed a new system to recover up to 60% of the energy used to heat water in a domestic supply system. The system, called the *Gravity Film Exchange* (GFX), uses hot greywater (water that has already been used and is moving down the drainage system) to preheat incoming cold water. According to Environmental Building News (1997), “Under ideal conditions, recovering that heat can actually double the effective efficiency of a water heater (p.6).”

The GFX system consists of a copper section of vertical drainpipe wrapped with a coil of ½” (13mm) copper supply pipe (see Figure 6.7). As hot water flows down the drain, it adheres to the sidewalls of the pipe, transferring heat through the copper to the incoming cold water. Under the right conditions, this transfer can heat incoming cold water from 50° F to 77° F (10°C to 25°C). The preheated cold water can feed into the water heater, and it can also go directly to the cold water tap of a sink or showerhead, where it reduces the amount of hot water drawn.

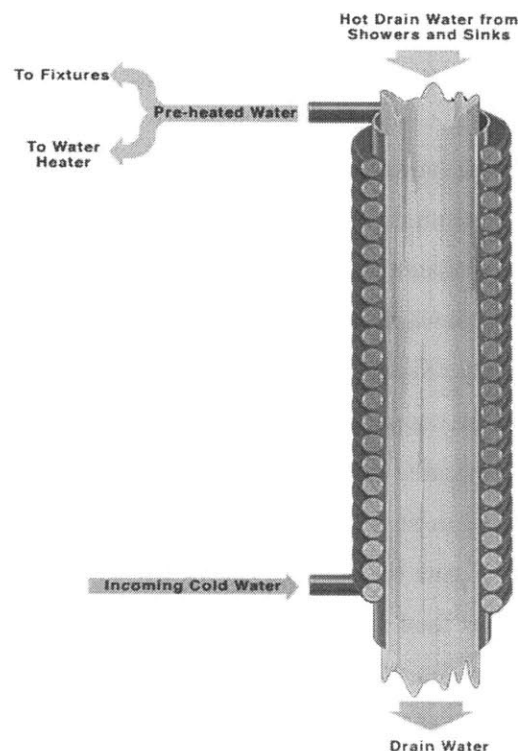


Figure 6.7: The GFX System Re-Circulating Hot Water (Vaughn, Inc., 1998)

predicts that, under ideal conditions, the effective output of an electric water heater can be tripled as a result of the GFX system's recycling of more than half of the energy in a shower (Vaughn, 1997).

The GFX system is primarily suited for recovering heat from fixtures that consume a large amount of hot water (e.g., showers, washing machines, dishwashers, etc.) because it relies on a continuous supply and use of hot water to preheat the cold water. In office sinks, hot water is used in small batches, and consequently does not provide a continuous supply of hot water. Nevertheless, the system presents some interesting installation implications that can be used to test the responsiveness of the plumbing model.

### **6.3.2 Modeling Implications**

#### ***Changes in the Process Flow***

The GFX system does not significantly affect the process flow for plumbing installation. DWV and supply piping still need to be installed for the system. The only difference is that, in areas where the re-circulation piping will be placed, the DWV stack that includes the GFX unit must be placed before the copper branch pipes leading to the GFX unit are attached.

#### ***Changes in Project Specifics***

##### Design Attributes:

The design specifics of the prototype plumbing system are drastically affected by the implementation of a re-circulation system. Both the DWV system and the network of supply piping for fixture groups have to be altered to accommodate the changes.

The drainage stacks that service the lavatories must be either 3" or 4" (76 mm or 102mm) copper piping to transfer the water's heat effectively. Separate ½" (13mm) copper supply branches split off of the cold water branches, and wrap around the copper drainage pipes before feeding into the lavatories (sinks). The GFX unit consists of a pre-fabricated section of copper drainage pipe that has copper supply tubing wrapped around it. The supply pipe can be wrapped around the drain line in one continuous loop or in two loops, connected in parallel (see Figure 6.7).

In addition to the reheating coils that feed directly into the shower, separate reheating lines could be used to feed the water heaters directly in order to minimize the time required to heat the water. In the system developed for the prototype building, however, the water heaters that are serviced by the GFX unit are located on the bottom floor. Even though water heaters are located on each floor of the prototype building for simulation purposes, in practice, the water heaters used for the GFX unit are located on the bottom floor (Vaughn, 1998). Any heat that could be gained from the soil stacks that service the upper

bottom floor (Vaughn, 1998). Any heat that could be gained from the soil stacks that service the upper floors would be lost by the time the water reached the water heaters. Therefore, the re-heating coils will only be installed for direct service to the fixtures.

The increased efficiency in the hot water system that results from the GFX system will create less of a demand for hot water. As a result, smaller hot water heaters (30-gallon heaters instead of 40-gallon) can be used for the building.

#### Resources:

The arrangement and allocation of resources for plumbing installation does not change for the installation of a GFX system. Because it is a modular unit, the GFX unit does not require any special equipment or crews to install. A team consisting of two journeymen can install the system with minimal instruction and a standard set of tools by connecting the system into the drainage stacks, and running copper supply piping through the ends of the supply tubing of the GFX unit.

#### Production Rates:

The re-circulation system requires two journeymen for installation at each floor. According to Vaughn Manufacturing, it should take approximately four hours to install the copper drainage pipe and copper supply pipe for each set of lavatories (1997). The 30-gallon electric water heaters will require less time to fill, but will require the same amount of time and resources to install as the 40-gallon heaters (Valante, 1998).

#### ***Changes in Project Dynamics***

The logical progress of the prototype building construction process is not impacted by the GFX system, because the installation of the GFX unit simply replaces the installation of a section of vertical drainage piping. The relationships among the supply piping installation activities remain unchanged as well, since the supply piping simply ties in to the ends of the GFX unit's copper tubing.

#### **6.3.3 Results**

The overall duration for the installation of a GFX-based plumbing system for the prototype building is 318 hours (40 days). The most significant change from the baseline system simulated in Chapter 5 occurs in the installation of risers and stacks, where the GFX system is connected (Table 6.8). The installation time for each stack that incorporated the GFX coils increased 50% to a rate of 1.5 hours per stack (Vaughn, 1998). The time increase was a result of the switch from Cast Iron, No-Hub connections to copper, soldered connections. Also, the GFX coils at the second and fourth floors

increased the overall time for installation, because the GFX units require an additional 30 minutes of installation time compared with the installation of standard DWV stacks (Vaughn, 1998).

	TIME	Time per Unit	Original Time per Unit
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	4 ft/hr
Complete Backfill	2 days	2 days	2 days
Horizontal Runs	6.5 days	50 LF/Day/Crew	50 LF/Day per Crew
Risers and Stacks	13 days	1 hr/stack, 1.5 hr/stack for GFX	1 hr/stack
Rough-In Fixtures	12 days	8 hrs/F.G., or 25 hrs per Fixture	8.5 hrs/F.G., or 27.5 hrs per Fixture
Finish Roof and Floor drains	1 day	.5 hr/drain (per team)	.5 hr/drain (per team)
Finish Fixtures	6 days	25 hr per Fixture Group (2 teams)	25 hr per Fixture Group (2 teams)
<b>Total Time on Site</b>	<b>40 days</b>		

**Table 6.8: Summary of Duration by Sub-Process for the GFX System**

Based on an overall duration of 40 days, the direct labor cost for installation is \$116,724, which is 11 % higher than the installation cost for the baseline system (see Appendix F). The additional cost results from keeping the plumbing crew on site for an additional four days.

The danger index for the GFX installation is 206, which is 7% higher than that for the baseline system (see Appendix E). The increase in the danger index is a result of the increased exposure to the dangerous conditions associated with the installation of DWV stacks and the installation of soldered connections.

As Figure 6.8 shows, the overall relationship among the major sub-processes in plumbing installation did not change significantly as a result of the GFX system. The only noticeable difference is that the slope of the “Risers & Stacks” line is steeper than the line in the baseline model. The increase is a result of the increase in the time required to install the copper soil stacks with GFX units.

As Table 6.9 shows, the use of the GFX system results in an increase in duration, cost, and danger index. However, the potential performance benefits of the GFX system are not included in the installation system. As discussed in section 6.3.1, the GFX system can significantly improve the energy efficiency of a plumbing system. The economic savings that may result from the use of this system should therefore be compared with the additional installation costs when assessing the feasibility of the GFX system.

	GFX System	Baseline	% Change
Duration	40 days	36 days	11%
Cost	\$ 116,724	\$ 104,976	11%
Danger Index	206	192	7%

**Table 6.9: Comparison Between the GFX and Baseline Plumbing Systems**

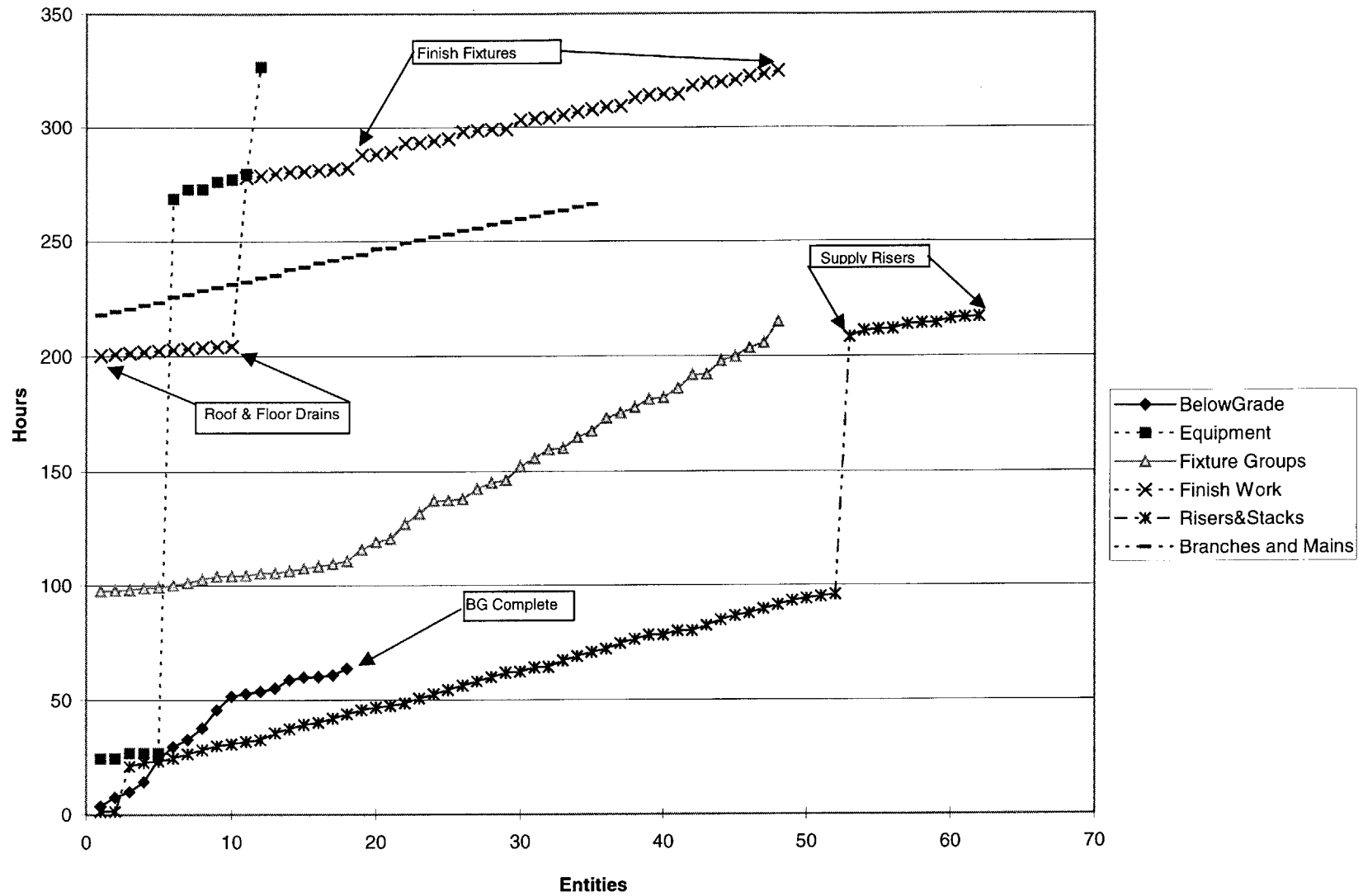


Figure 6.8: Progress of Plumbing Installation for the GFX System

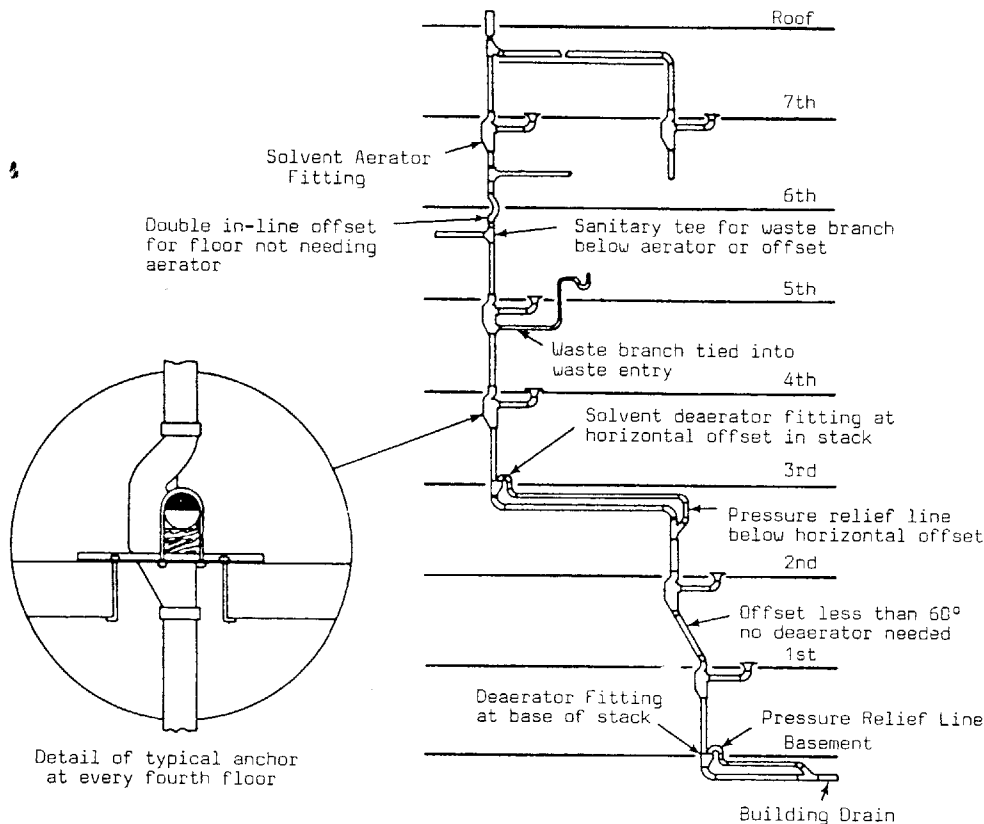
## **6.4 Innovation #4: Sovent® Aerators**

### **6.4.1 Description**

Developed about two decades ago by a Swiss plumber named Fritz Sommer, the Sovent drainage system combines vent and drainage systems, thereby eliminating the need for vent stacks. The system has four major design elements: a copper DWV stack, a copper Sovent aerator fitting at each floor level where fixtures are present, horizontal branches, and a copper de-aerator fitting at the base of the stack and at horizontal offsets. The aerator and de-aerator provide means for self-venting the stack. A properly arranged Sovent system can handle the same fixture load as a conventional drainage stack of the same diameter, but without the need for the separate vent stack required for traditional systems (Merritt & Ambrose, 1990). Figure 6.9 shows the arrangement of a Sovent aerator system for a typical building.

In conventional systems, vent stacks are used to supply air to drainage branches to prevent destruction of the trap seals through suction (see Chapter 4). In the Sovent system, aerators are used to prevent these suction effects. Aerators reduce the velocity of both liquid and air in the stack, by mixing the wastewater from the branches with the air in the stack. They also prevent the cross section of the stack from filling with a plug of water. The de-aerators are used at the bottom of the waste stacks to separate the airflow in the stack from the wastewater.

Although the Sovent system was originally developed almost twenty years ago, it is just beginning to gain acceptance in the United States. Up until 1988, the system did not meet the conventional code requirements as they were listed in the Uniform Plumbing Code, and so plumbers and designers have only started to use the system over the past ten years.



**Figure 6.9: Sovent® Aerator System (Merrit & Ambrose, 1990)**

## 6.4.2 Modeling Implications

### *Changes in the Process Flow*

The overall plumbing installation process will not have to change to incorporate the Sovent drainage system, but the processes associated with the installation of DWV stacks will be affected.

The processing time for the installation of DWV stacks will be reduced, since vent stacks are not necessary for a Sovent system. However, in the installation of drainage stacks, an additional connection activity is required just underneath each floor slab to install an aerator like those shown in Figure 6.8. For each stack entity, one aerator connection activity will be required.

An additional activity is required to represent the installation of the de-aerator at the base of each soil or waste stack. The activity must be performed on the first-floor stack entities.

### ***Changes in Project Specifics***

#### **Design Attributes:**

The design specifics for the building's DWV system change significantly for the Sovent system. First, similar to the GFX system, the material used for both the horizontal and vertical drainage system must be copper to accommodate the aerator connections. Secondly, loop vents are no longer needed to vent the individual fixtures, since the fixtures are vented through the horizontal drainage lines. The pipe diameters of the horizontal drainage lines must be increased to allow more airflow, but stack diameters can remain the same as those used for the prototype building.

An aerator is required on the stack at each level where a horizontal waste branch drains into the stack. At any floor where an aerator fitting is not required, the stack should have a double inline offset to decelerate the flow (see Figure 6.9).

#### ***Resources:***

The Sovent drainage system does not require any additional tools or crews to install. A team of two journeymen can install an aerator or de-aerator onto a stack with a standard wrench.

#### **Production Rates:**

Installation times for drainage stacks will increase slightly with the inclusion of the aerator fittings. Accurate installation data on the aerator fittings, which are similar to a couple fitting for stacks, was unavailable for this research. As a result, for simulation purposes, the installation will be treated as if the aerator was a coupling that two plumbers could install in 20 minutes. Similarly, the de-aerators are estimated to take two journeymen 30 minutes to install, since the de-aerators are larger and slightly more complex than the aerators.

Additional inspection time must be allotted to insure that the aerators are functioning properly. According to several city building codes (Salt Lake City Plumbing Code, 1997), city inspectors are required to test each aerator and de-aerator fitting for leaks and proper fitting. For simulation purposes, this requirement is estimated to add an additional 3 hours to the inspection process.

### ***Changes in Process Dynamics***

Sovent drainage systems may have a positive effect on the overall progress of the building, because there won't be any vent stacks to interfere with the other building systems. Additional time will have to be allotted for inspection of the Sovent system though, because it is not a completely gravity-based system like traditional systems.



Many municipalities are just starting to allow Sovent systems (Salt Lake City Plumbing Code, 1997), so they are very thorough in their inspections. In Salt Lake City, for example, section 18.56.100 of the Plumbing Code requires that “The proprietor (designer) of the Sovent system shall certify at the completion of the installation that they have inspected the system and that the system complies with the approved plans.” This certification is required in addition to the inspection performed by the municipality itself.

### 6.4.3 Results

The computer-based simulation model determines the overall duration for the plumbing installation using the Sovent® Aerator system to be 242 hours (30 days). This represents a 17% reduction in total installation time from the original plumbing system simulated in Chapter 5. The most significant changes occurred in the installation of DWV stacks and in the rough-in for room systems. Since vent stacks are not required for the Sovent system, the overall installation time for DWV stacks dropped 9% to 10 days. The installation time for the remaining stacks, however, increased 50% from a rate of 1 hour per stack to a rate of 1.5 hours per stack. The increased time per stack resulted from the inclusion of the aerators for soil stacks. Fixture groups were installed at a 25% faster rate (6 hours per fixture group), because vents did not have to be installed for each fixture. Table 6.10 summarizes the results of the simulation for the Sovent system.

	TIME	Time per Unit	Original Time per Unit
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	4 ft/hr
Complete Backfill	2 days	2 days	2 days
Horizontal Runs:	6 days	50 LF/Day/Crew	50 LF/Day per Crew
Risers and Stacks	10 days	1.5 hr/stack	1 hr/stack
Rough-In Fixtures	6 days	6 hrs/F.G., or 2 hrs per Fixture	8.5hrs/F.G., or 2.75 hrs per Fixture
Finish Roof and Floor drains	1 day	.5 hr /drains (per team)	.5 hr /drains (per team)
Finish Fixtures	6 days	2.5 hr per Fixture Group (2 teams)	2.5 hr per Fixture Group (2 teams)
<b>Total Time on Site:</b>	<b>30 days</b>		

**Table 6.10: Summary of Duration by Sub-Process for Sovent® System**

The 30-day duration for the installation of the plumbing system results in a direct labor cost of \$89,100, which is 15% less than the direct labor cost for the original system (see Appendix F).

Worker exposure to dangerous conditions did not change significantly because the savings in time took place in the relatively safe activity of roughing in the room systems. The overall danger index for the Sovent® system was 192, which is the same as that for the original system.

Figure 6.10 illustrates the progress of the various plumbing installation sub-processes using the Sovent® system. As the figure shows, the relationship among the sub-processes does not change significantly from the original plumbing system. The only significant difference is in the slope of the “fixture group rough-in” line, which is less steep than the line in the original simulation. This reduction in slope results from the removal of vents from each fixture. Table 6.11 summarizes the savings in cost, duration, and safety that result from the Sovent® innovation.

	Sovent System	Baseline	% Change
Duration	30 days	36 days	-17%
Cost	\$ 89,100	\$ 104,976	-15%
Danger Index	192	192	0%

**Table 6.11: Comparison Between the Sovent® and Baseline Plumbing Systems**

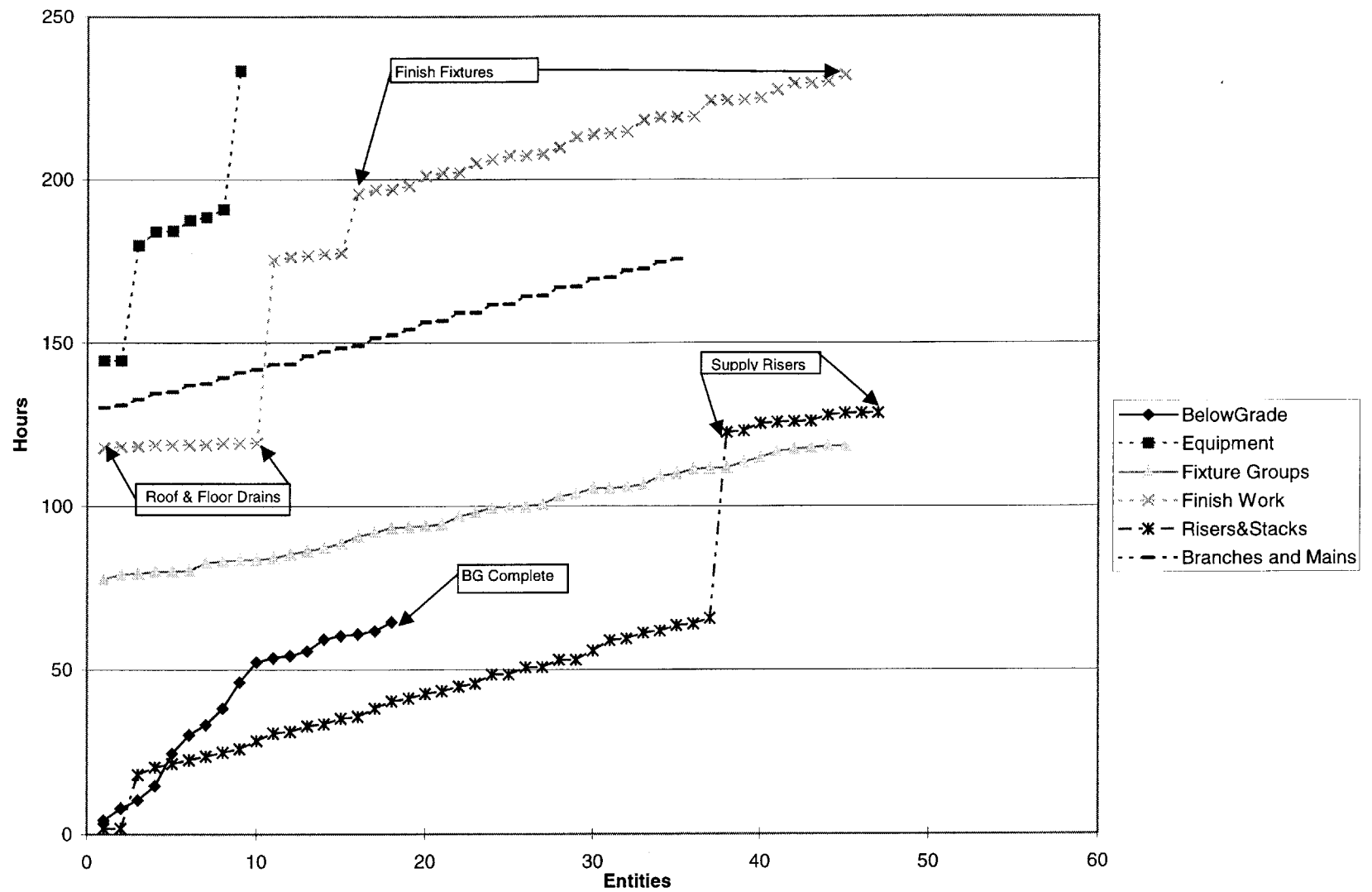


Figure 6.10: Progress of Installation for the Sovent Plumbing System

## 6.5 Summary of Results

The innovations tested in this research affect the overall installation process for plumbing and fire protection systems in a variety of ways. The effects on time, cost, and worker safety are summarized in Table 6.12 below.

Simulation	Overall Duration	% Change from Baseline	Cost	% Change from Baseline	Danger Index	% Change from Baseline
<b>Baseline Plumbing</b>	<b>36 days</b>	—————	<b>\$ 104,976</b>	—————	<b>192</b>	—————
Flexible Piping	28 days	-22%	\$ 83,580	-20%	135	-34%
Grooved Fittings	32 days	-11%	\$ 91,860	-13%	138	-29%
GFX System	40 days	11%	\$ 116,724	11%	206	7%
Sovent Aerators	30 days	-17%	\$ 89,100	-15%	192	0%

**Table 6.12: Summary of Results for Innovations**

The flexible piping system, when incorporated into the prototype building, generates the greatest savings in time, cost, and safety. The reduction is mainly the result of the faster speed at which plumbers can install horizontal supply lines for fixtures with flexible piping, despite the additional activities required to install manifolds. The flexible piping system also results in a more energy efficient system in terms of hot water usage, and is a much easier system to repair compared with the traditional rigid copper system.

Similar to the flexible piping system, the use of grooved fittings significantly reduces the time required to install or repair horizontal supply piping. Grooved fittings are also safer to install than soldered fittings, which leads to a reduction in worker exposure to dangerous conditions. Duration, cost, and safety benefits are possible with grooved fittings for both plumbing and fire protection systems. Table 6.13 below summarizes the benefits associated with grooved fittings when compared with threaded connections for fire protection installation.

Simulation	Overall Duration	% Change from Baseline	Cost	% Change from Baseline	Danger Index	% Change from Baseline
<b>Baseline Fire Prot.</b>	<b>48 days</b>	—————	<b>\$ 132,600</b>	—————	<b>221</b>	—————
Threaded Fittings	53 days	10.4%	\$ 146,410	8.9%	232	4.9%
Grooved Fittings	46 days	-4.3%	\$ 127,000	-4.2%	210	-4.9%

**Table 6.13: Summary of Results for Fire Protection Installation**

The GFX system requires additional time to install when compared with the baseline plumbing system, and consequently costs more to install as well. However, the workers' exposure to danger is only increased slightly, since the actual installation of the GFX units is a relatively safe activity. The increase in duration and cost associated with installation of the GFX, however, may be countered by the potential savings in energy costs that can result over the lifetime of the system.

The use of Sovent® aerators in place of vent stacks significantly reduces the time required to install DWV stacks for the plumbing system. As a result, the overall time and cost associated with plumbing installation is reduced. The system is relatively new for plumbing, however, so the performance of the aerators over several years is still undetermined.

## **6.6 Simulation of a Combination of the GFX, Sovent®, and Grooved Fittings Innovations**

Since both the GFX and Sovent® systems require copper pipe sections for the DWV stacks, it may be possible to combine the two innovations into one system. The combination system could take advantage of the possible energy savings associated with the GFX system, while simultaneously reducing installation costs through the use of Sovent aerators. In fact, additional benefits are possible if a third innovation, the use of grooved fittings, is included in the combination system to reduce the time required to connect the copper pipe sections.

The only significant implications of the combination system occur in the project specifics. In this system, the number and location of the DWV stacks remains consistent with those associated with the Sovent system, where vent stacks are no longer used. The drainage stacks associated with the fixture units, however, will include aerators at each floor, as well as GFX units at every other floor. In addition, the stacks will be copper, with grooved fittings at each connection. As in section 6.2, all soldered connections in the entire plumbing system will be replaced by grooved fittings.

The modeling implications of the combination system are the same as those described for each innovation in the previous sections. The process flow will be impacted by the additional activities associated with the installation of the GFX units and aerators.

### **6.6.1 Results for the Simulation of the Combination Plumbing System**

The combination of the Sovent, GFX, and grooved fittings innovations results in an overall savings of 10 days in terms of installation time for the plumbing system. Direct labor costs, which are proportional to installation time, are reduced by 26% to a cost of \$78,050. The danger index is reduced to 136 (29% lower than baseline). Table 6.14 summarizes the duration of the major installation sub-processes for the combination system.

	TIME	Time per Unit	Original Time per Unit
Trench and Emplace Below Grade Piping	5.5 days	4 ft/hr	4 ft/hr
Complete Backfill	2 days	2 days	2 days
Horizontal Runs:	3.5 days	90 LF/Day/Crew	50 LF/Day per Crew
Risers and Stacks	10 days	1.5 hr/stack	1 hr/stack
Rough-In Fixtures	5 days	5.5 hrs/F.G., or 2 hrs per Fixture	8.5hrs/F.G., or 2.75 hrs per Fixture
Finish Roof and Floor drains	1 day	.5 hr /drains (per team)	.5 hr /drains (per team)
Finish Fixtures	6 days	2.5 hr per Fixture Group (2 teams)	2.5 hr per Fixture Group (2 teams)
<b>Total Time on Site:</b>		<b>26 days</b>	

**Table 6.14: Summary of Duration by Sub-Process for the Combination System**

The overall duration for the installation of the combination system is 208 hours (26 days), which is a 28% savings in time from the baseline system. The most significant changes from the baseline system occurred in the rough-in of the fixture groups, where vents were no longer needed as a result of the Sovent aerators. Rough-in duration for the fixture groups was also reduced through the use of grooved fittings instead of soldered connections for the supply lines. The installation of the DWV stacks took slightly less time than it did for the baseline model. The reduction in the number of stacks that resulted from the aerators and the reduction in connection time that resulted from the grooved fittings reduced stack installation time. However, the installation of the aerators and GFX units added time to the stack installation process, resulting in a minimal net change in stack installation time.

Table 6.15 summarizes the significant savings in costs and duration associated with the combination system, and also shows the decrease in danger index that results. As the table indicates, the combination system saves more in terms of cost and duration than any single innovation. The primary reason for the significant reduction in the danger index value (29%) is the use of the grooved fittings, which are safer to install than soldered connections.

	Combination System	Baseline	% Change
Duration	26 days	36 days	-28%
Cost	\$ 78,050	\$ 104,976	-26.0%
Danger Index	136	192	-29%

**Table 6.15: Comparison Between the Combination and Baseline Plumbing Systems**

Figure 6.11 illustrates the process flow for the installation of the combination system. As the figure shows, the relationships among the installation sub-processes did not change significantly as a result of the combination of the three innovations. The overall reduction in time and cost, however, indicates the significant potential of the innovations if they can be combined effectively.

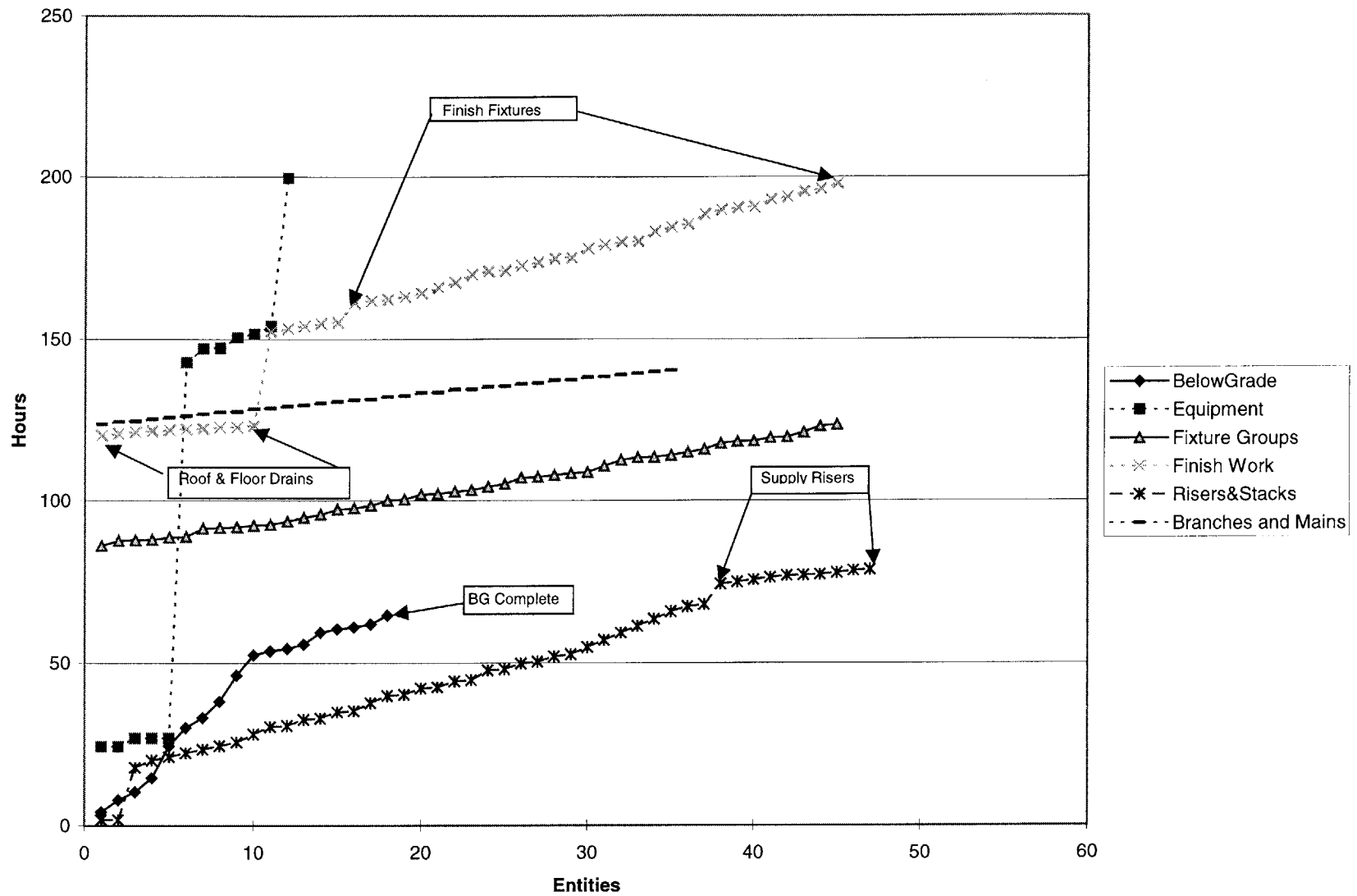


Figure 6.11: Progress of Installation for Combination Plumbing System





## 7 Conclusions

### 7.1 Summary of Findings

The overall objective of this research was to develop computer-based dynamic process models capable of simulating the installation of plumbing and fire protection systems. The models can be used to evaluate the impact of innovations and design changes on the installation processes.

The majority of the plumbers interviewed in this research have never attempted to formally characterize the installation process; they have instead relied on “hand’s on” learning to formulate and plan the necessary activities required to install a system. In contrast, the models developed here provide a “formal” characterization of the installation processes by clearly identifying the specific activities required, as well as the relationships among those activities. The incorporation of this characterization into a computer model provides owners, designers, and builders with an accurate methodology for analyzing options at the design phase without the need for full-scale experiments.

The majority of mechanical contractors in the United States have relied on traditional planning tools like the Critical Path Method (CPM) and the Quantity Take-Off Method for assessing the cost and duration associated with a particular project (Valante, Dowd, 1998). The methods are useful for estimating material requirements and for providing a general sequence of work activities. However, they do not attempt to represent the installation process at the specific task level, where innovations and design changes may have a significant impact. In response, three different simulation approaches (queuing models, graphic-based models, and dynamic process models) are being developed in an attempt to model the specific task level impacts of design and process alternatives. Queuing models track the flow of resources among different activities and are useful for modeling cyclic and repetitive processes. Graphic-based models build on the queuing method of tracking resources, but they also attempt to address spatial and time constraints that arise throughout the construction process. Dynamic process models track the flow of entities (components, materials, or information) through a process. As a result, they are particularly useful in modeling non-repetitive and flexible processes like plumbing, where the relationships among activities change throughout the simulation.

The dynamic process approach was chosen to simulate the installation of plumbing and fire protection systems. Detailed information on the specific activities and design characteristics associated with the systems was gathered to formally characterize the process. Technical literature, construction site visits, and interviews with industry members served as the basis for the information. Interviews were also used after the models were developed to verify the models’ validity, accuracy, and reliability.

Based on the information gathered, the plumbing installation process is divided into five major sub-processes: below-grade installation, equipment installation, vertical piping installation, horizontal piping rough-in, and finish work. The fire protection process is similar, but does not require below-grade installation.

As the processes were identified and transferred to flow diagrams, the flexibility of plumbing and fire protection installation became very apparent. During the interviews, contractors often said that they have a particular order in which they prefer to perform the sub-processes. However, the contractors also revealed that the processes could be performed in any particular order if resource or outside-system constraints dictate. Consequently, “bottlenecking” is not a significant problem for the systems, since the resources (crewmembers) can perform a variety of different activities at any given time. Plumbing and fire protection installations are also more flexible because they are not as spatially constrained as other processes like steel erection and concrete construction. For example, steel erection is limited in terms of the rate at which it can be installed, because too many resources would lead to spatial conflicts. Spatial conflicts in plumbing and fire protection result more from competing systems like HVAC and electrical systems rather than from other plumbing systems.

Once the installation processes had been identified and characterized in terms of process flow, project specifics, and project dynamics, the computer-based simulation model was developed using a commercially available software package called SIMPROCESS®. The model was developed with several goals in mind. First, the model needed to provide valid, reliable, and accurate results with regards to the cost, duration, and safety impacts of a particular system installation. Second, the model needed to be responsive and flexible enough to allow the user to assess the impacts of a wide range of design and installation innovations.

Once developed, the models were tested through the simulation of the installation of plumbing and fire protection systems for a “prototype” building. Results from the simulations indicate several interesting characteristics about the installation processes. First, the flexibility of the systems in terms of resource allocation allows for several different activities to be performed simultaneously. The quantity of resources available therefore has a relatively higher impact on the time required to complete installation when compared with other construction processes.

The simulations for the systems also indicated where innovations and design changes could have the most significant impacts on the overall process. In horizontal piping installation, small changes in the connection type used for the piping led to large fluctuations in overall installation times for the horizontal systems. Changes in hanger spacing led to similar results for the horizontal piping installation process. This effect was evidenced in the fire protection system installation, where the majority of the installation process involves installation of the horizontal branches and mains. In contrast, significant changes in

smaller activities like fixture installation do not have as large of an impact on the overall cost and duration of the project, since the activities are not repeated as often.

The simulation models were also used to assess four recent innovations in plumbing systems. The results of the simulation verified the observations gathered from the prototype building, and were useful in comparing the impacts of the innovations on the plumbing installation process.

The simulations run for the innovations indicate that the innovations have the potential to significantly impact the cost, time, and safety of a plumbing installation project. Flexible piping systems and grooved fittings proved to have the most impact on the installation for horizontal supply piping. Systems that require large horizontal piping runs will therefore benefit the most from these innovations. Sovent® aerators, however, reduce the time and costs associated with DWV stack installation, and do not affect the supply installation process at all. Finally, the GFX system, which may save owners and tenants up to 60% in energy costs associated with hot water heating, cost 11% more to install than a standard system. If the GFX is properly used, the benefits associated with the performance of the system may outweigh the installation costs. Also, a combination system that includes the GFX, grooved fittings, and Sovent® aerators can reduce duration and costs significantly, while also reducing worker exposure to dangerous conditions. Further research should be conducted on the performance implications of combining these innovations, however, before they are combined in practice.

## **7.2 Conclusions**

The computer-based dynamic process models developed in this research represent a completely new method for simulating the installation of plumbing and fire protection systems. Because the models simulate the installation processes at the specific task level, the overall effects of task-specific innovations like alternative pipe connections can be assessed more accurately.

The plumbing and construction industry as a whole can benefit greatly from the models. Plumbing contractors can use the simulations to assess the implications of various resource allocation alternatives on the overall cost and duration of a project. The contractors can also evaluate the impacts of various installation innovations (e.g., alternative pipe connections) on labor costs. Safety impacts of various alternatives can be addressed as well through the use of danger indexes that compare worker exposure to dangerous conditions for each alternative. Finally, the models can identify the areas within the installation process where innovations could have the most significant impacts.

Project managers can use the simulation models to assess the impacts of their site management decisions on the overall project. For example, scheduling alternatives between plumbing and other

service systems (e.g., HVAC, electrical, communications) can be analyzed accurately before a final decision is made.

Owners and designers will be able to analyze and compare the economic benefits of various design alternatives and innovations more easily through the simulation models. The actual initial investment associated with installation of a particular design alternative, for example, can be predicted more quickly through simulation. The initial investment can then be compared with lifecycle costs to assess the feasibility of the design alternative.

The plumbing and fire protection models developed in this research will be combined with models of other building systems to create a “meta-model” that will be used to simulate the overall construction of a building. To date, models have been developed for steel erection, cast-in-place concrete construction, exterior enclosure, and HVAC installation. The meta-model will allow users to assess the interactions among adjacent systems on each other’s installation processes.

Further research should be conducted on the feasibility of incorporating the simulation models into a graphic design package. Combination with a design package will allow design teams to automatically assess the installation impacts of their designs. Designers and contractors could also combine their material and labor cost estimates into one step.

The plumbing and fire protection industries have been notorious for their apparent aversion to innovation. The models developed here have proven to be accurate, reliable, and responsive; they will help to propel the construction industry into the future by reducing the barriers that have led to stagnation.

## **Appendix A: Process Flow Diagrams for Plumbing Installation**

## Flow Diagrams

**Flow Diagrams** are a visual representation of the construction process. They try to capture each of the tasks involved, the sequence of these tasks, and the repetition and cycling of groups of tasks.

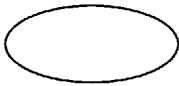
In the attached flow diagrams, the following shapes are used:



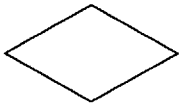
Rectangles represent an activity



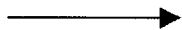
Double-bordered Rectangles represent a link to a flow diagram on another page.



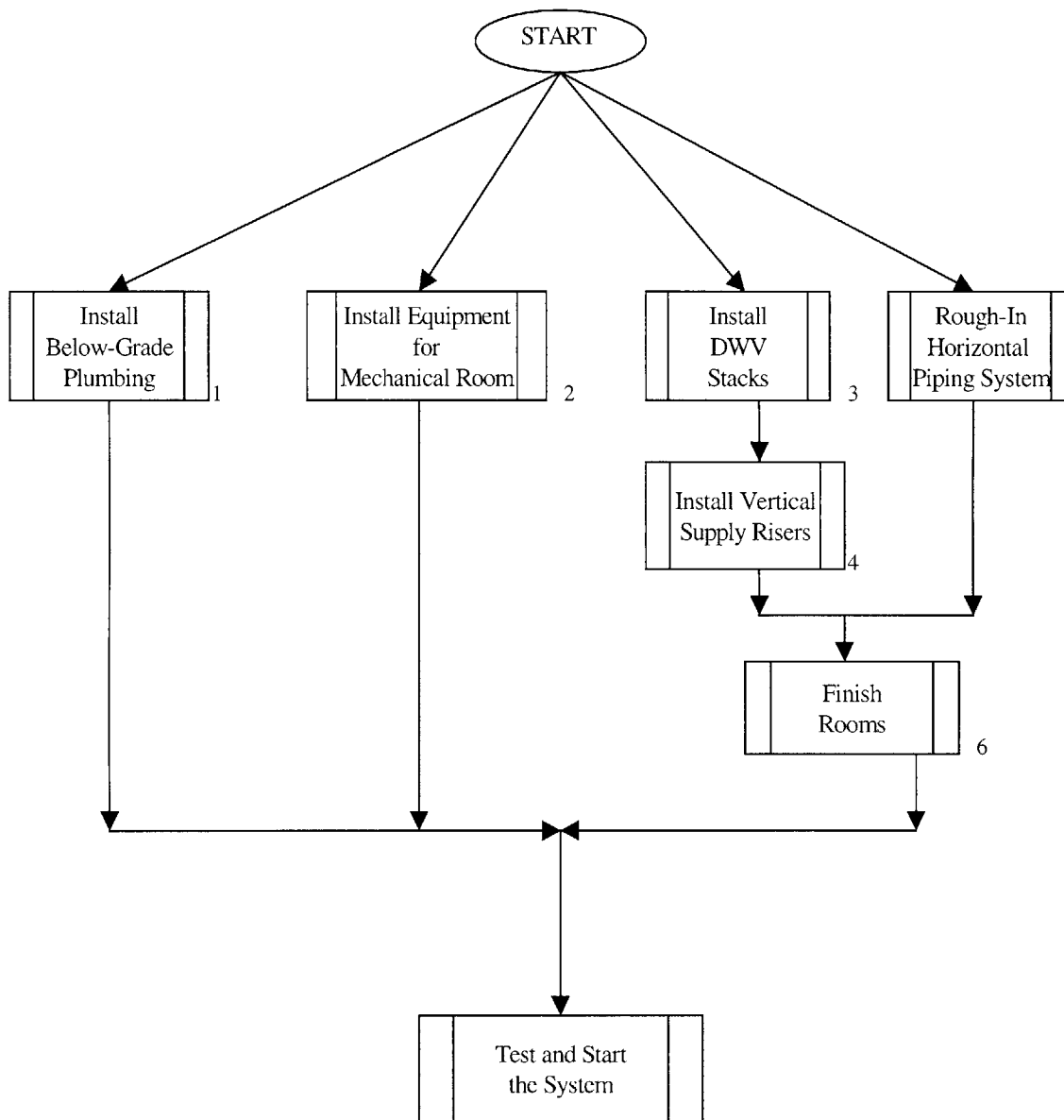
Ellipses mark the start and end of flow diagrams.



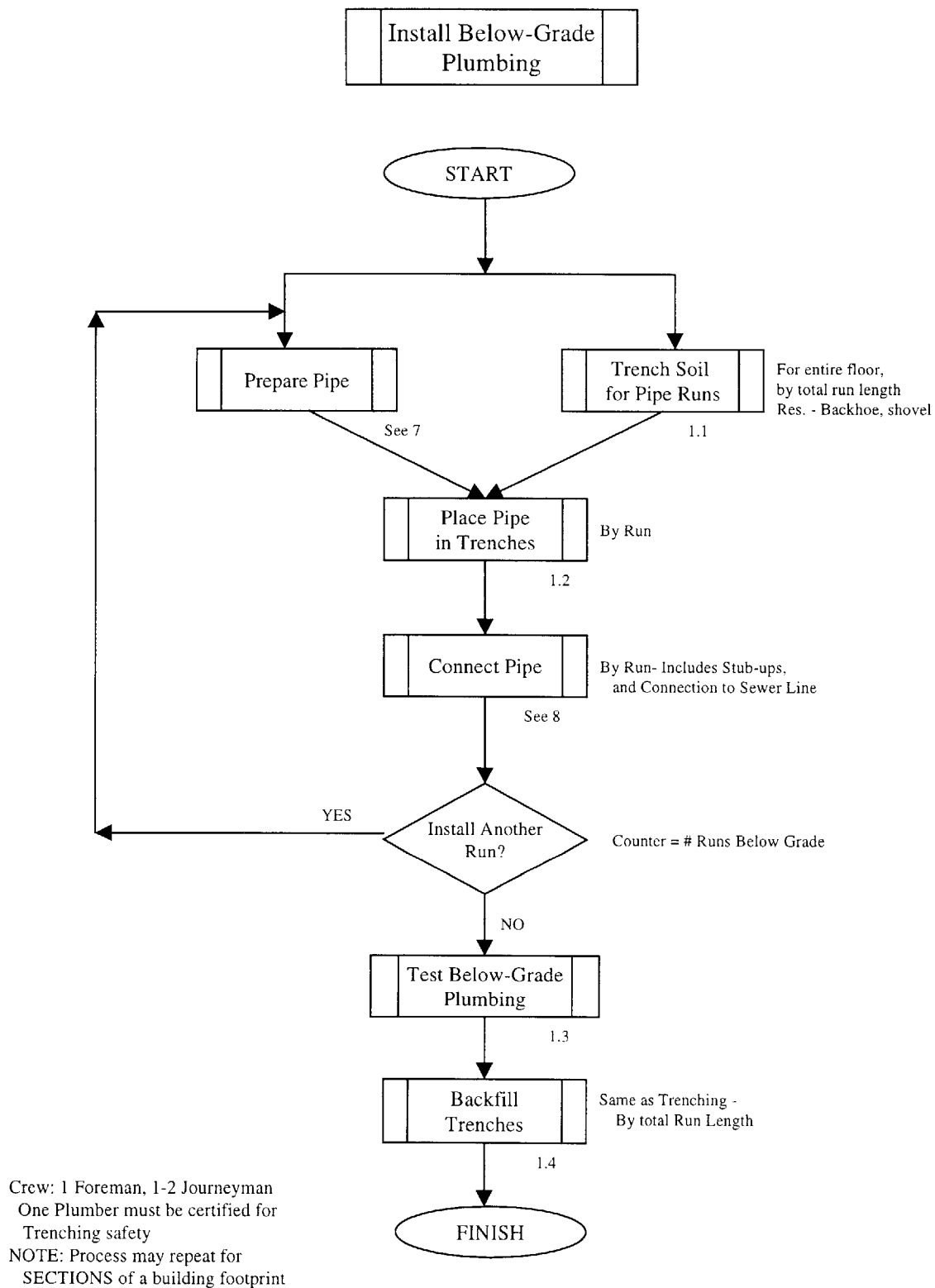
Diamonds represent a decision branch. They include counters for repetitive tasks.



Arrows are used to link different activities or sub-processes together

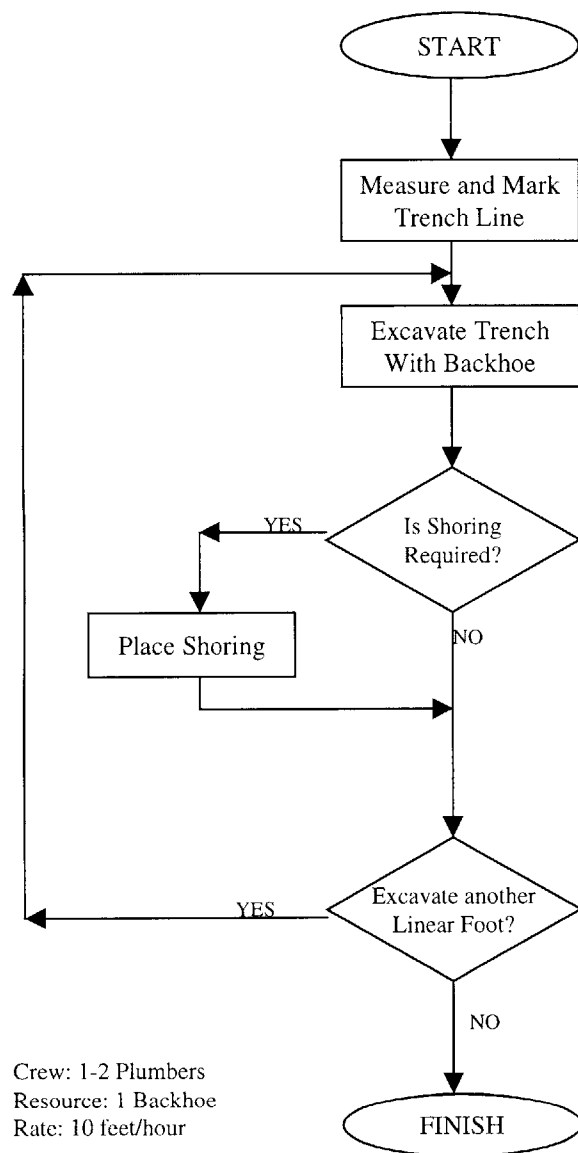


**Figure A.1: Overall Process for Plumbing Installation**

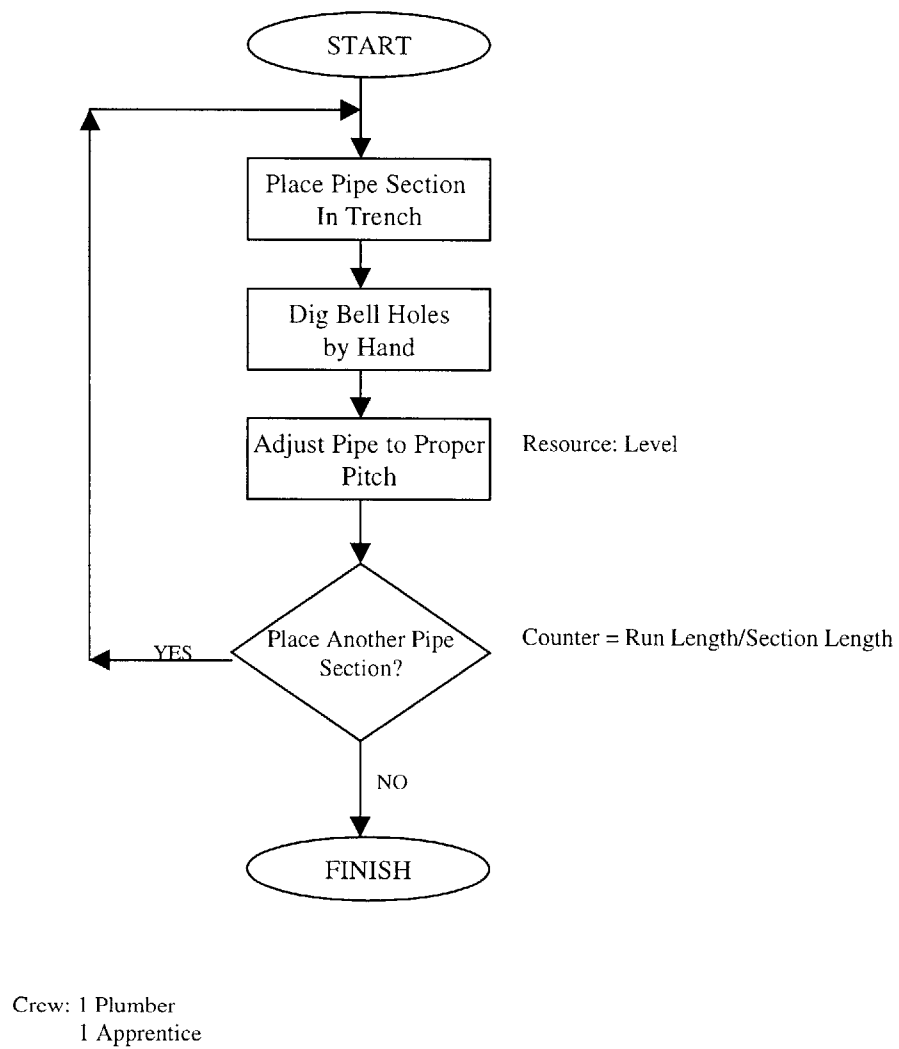


**Figure A.2: Installation Process for Below-Grade Plumbing**

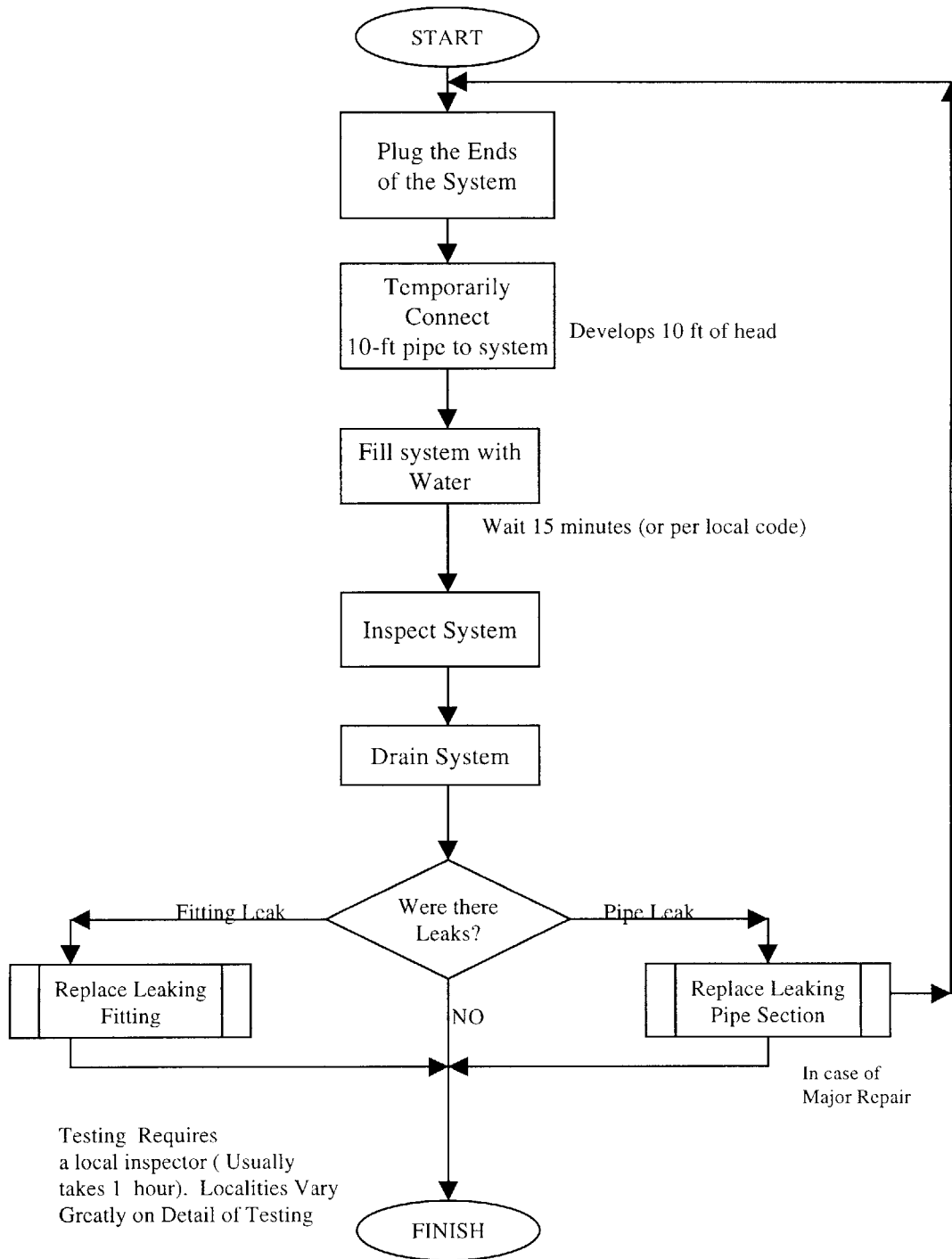




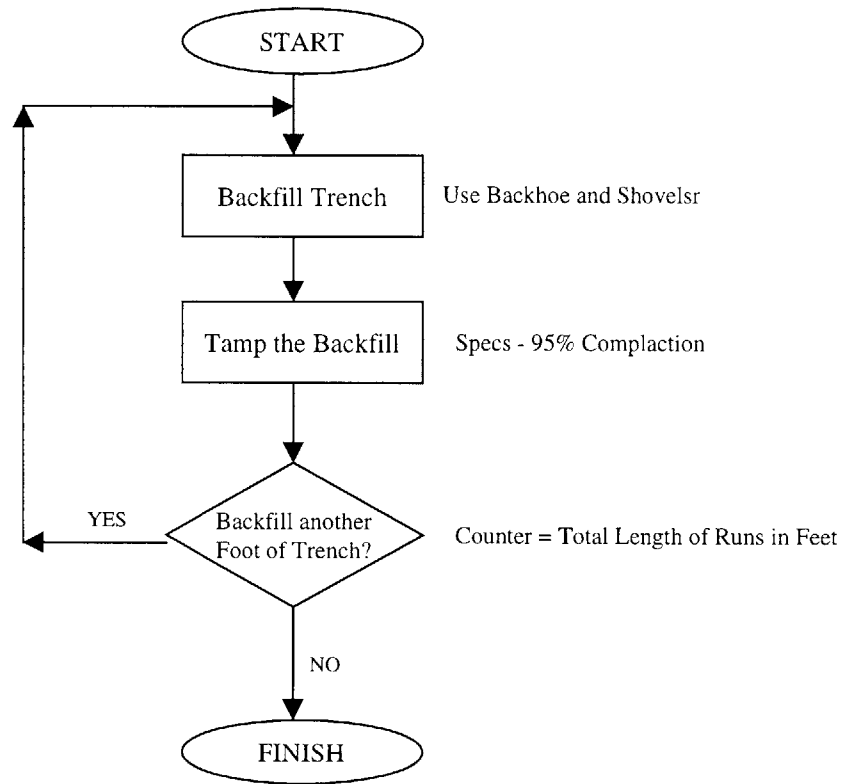
**Figure A.3: Trench Soil for Piping Runs**



**Figure A4: Place Pipe in Trenches**

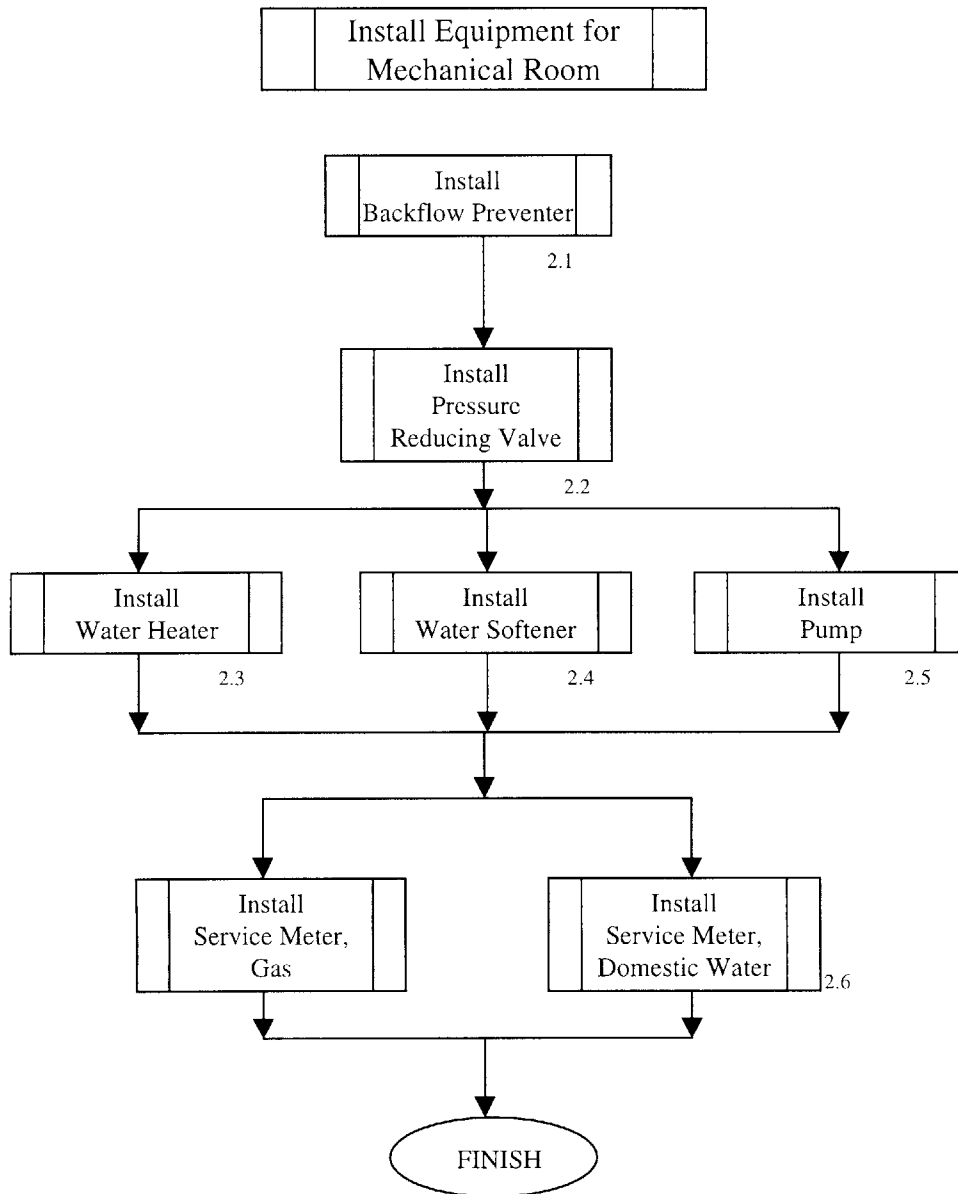


**Figure A.5: Test Below Grade Plumbing**

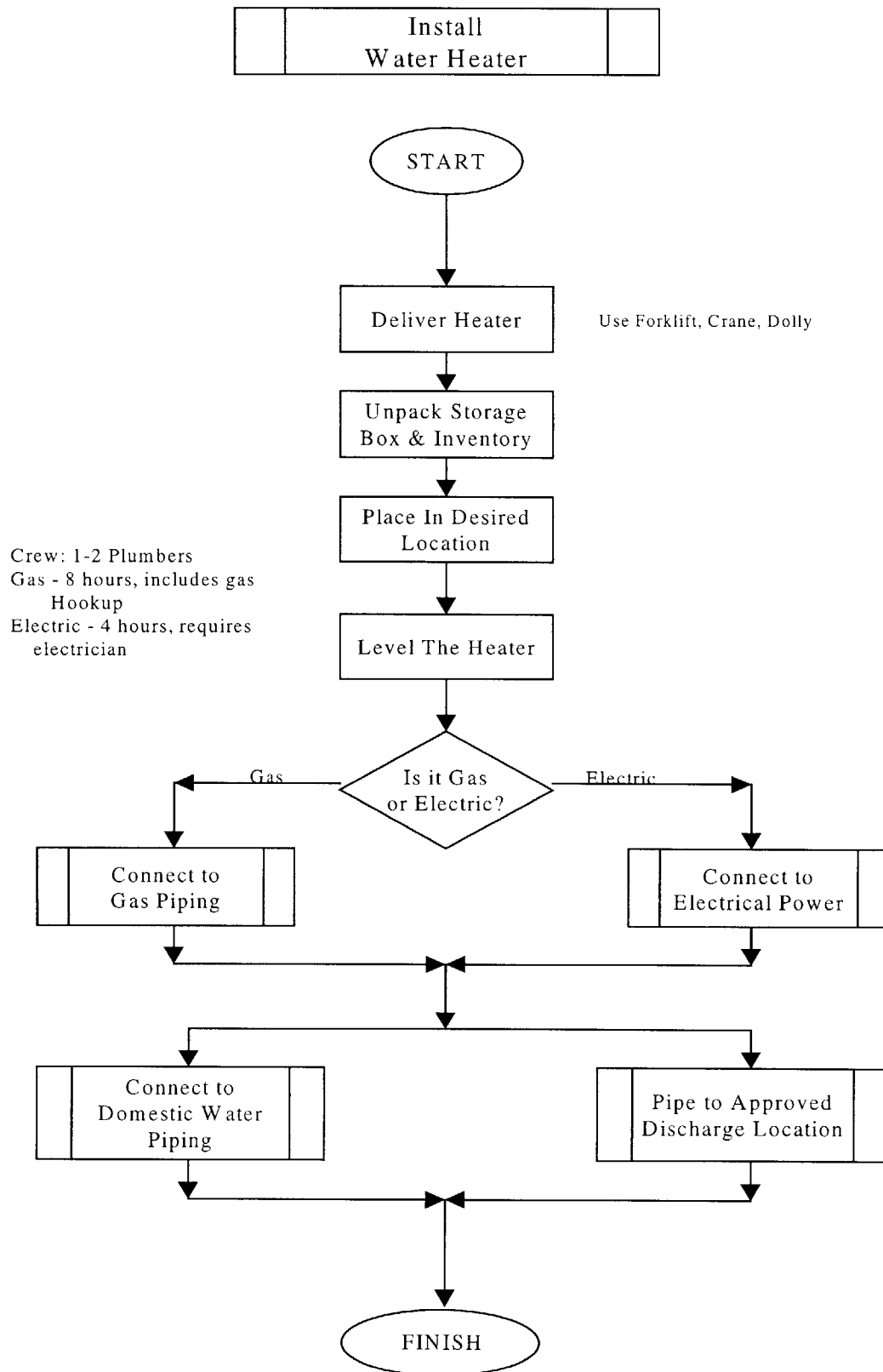


**Figure A.6: Backfill Trenches**

## 2

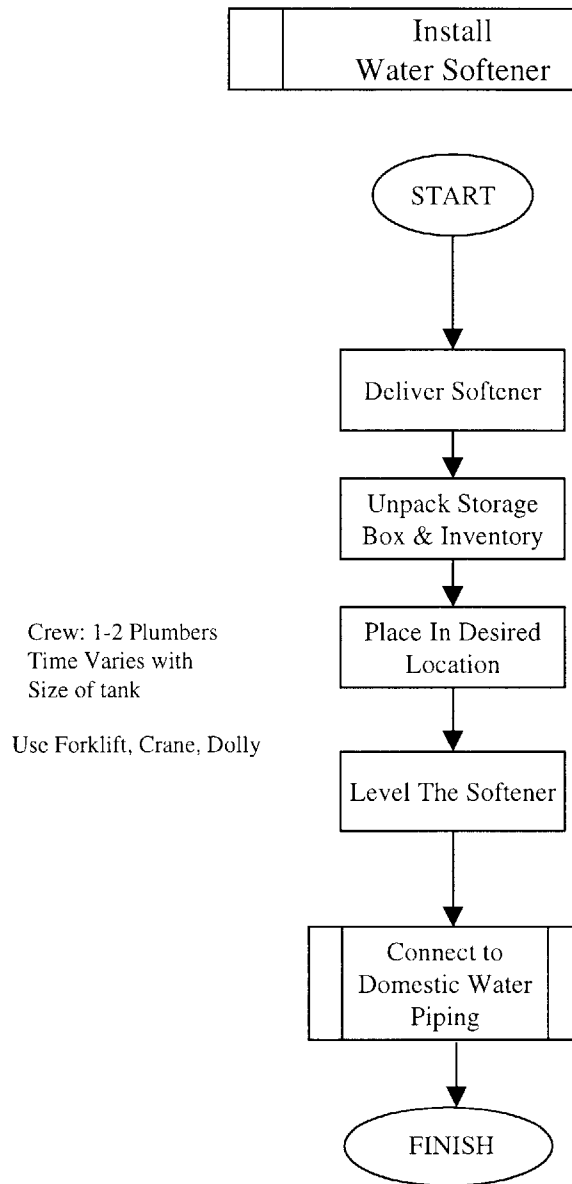


**Figure A.7: Install Equipment**



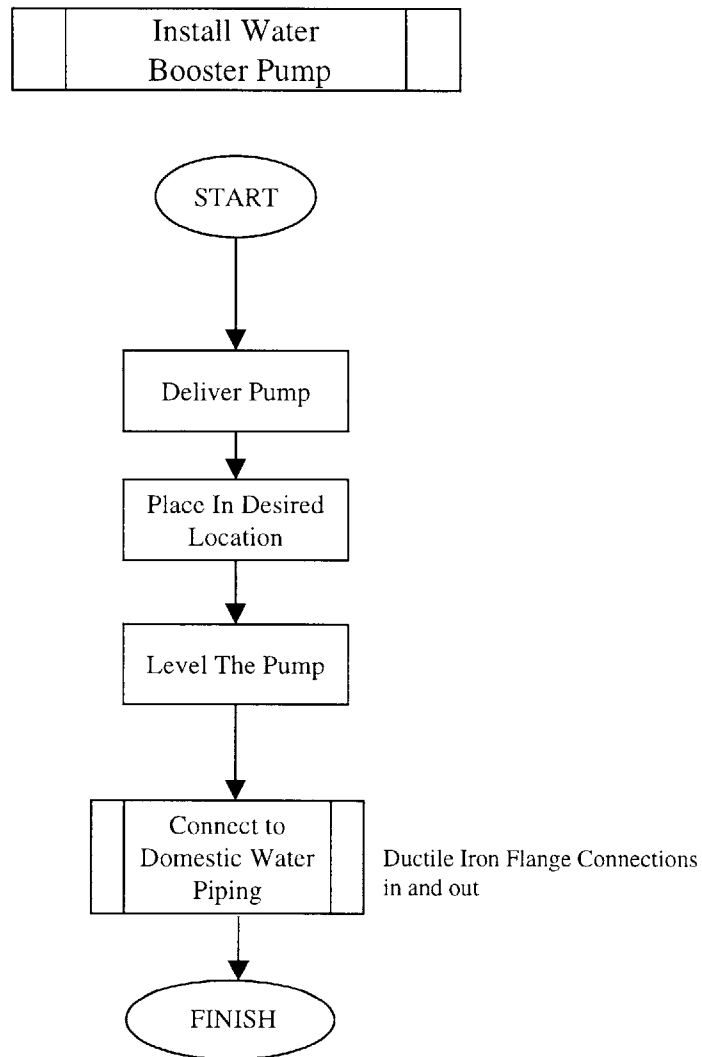
**Figure A.8: Install a Water Heater**

## 2.4



**Figure A.9: Install Water Softener**

## 2.5



Crew: 2 Journeymen  
Installation Time: 2 hrs

Use Forklift, Crane, Dolly

**Figure A.10: Install Water Booster Pump**



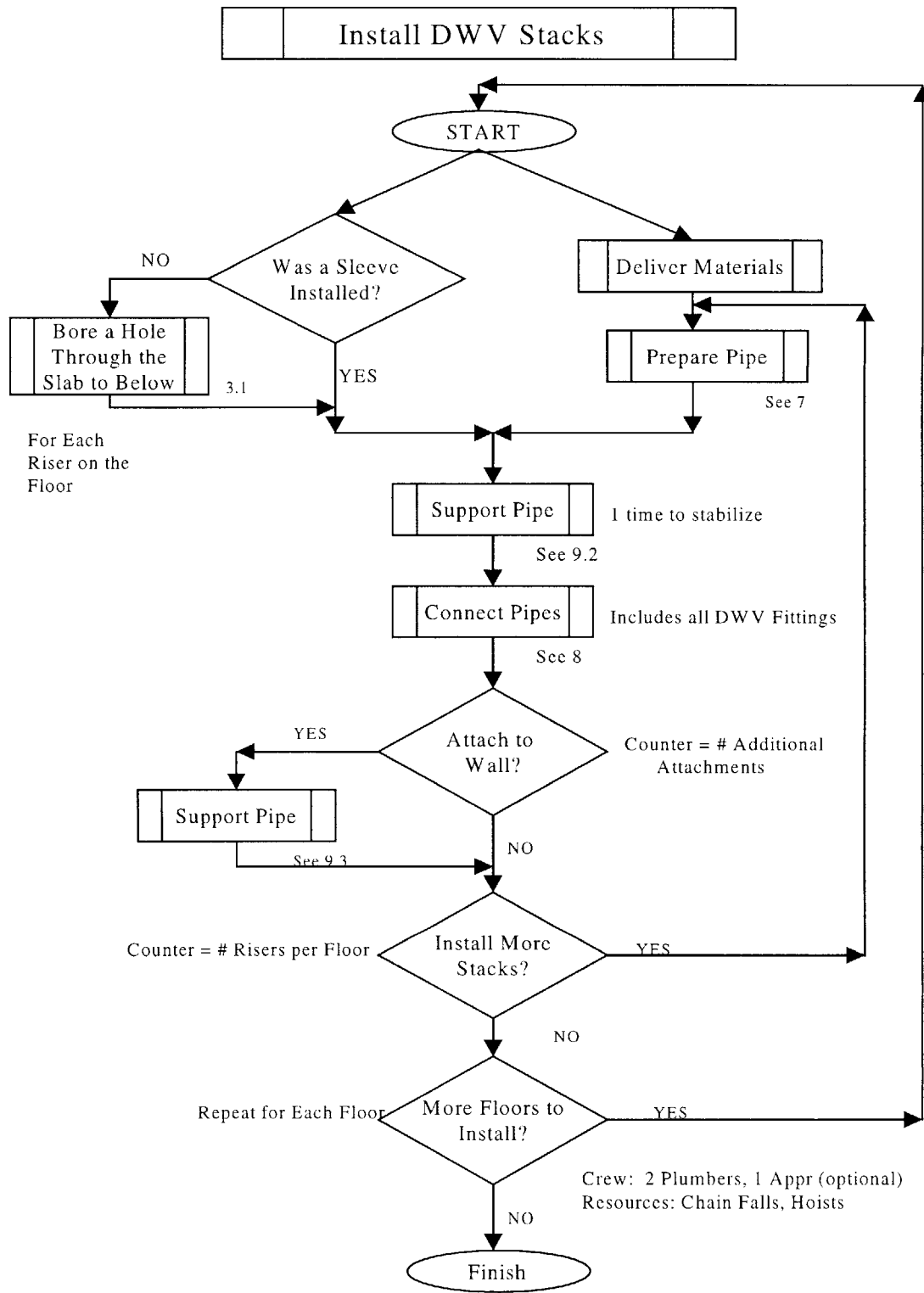
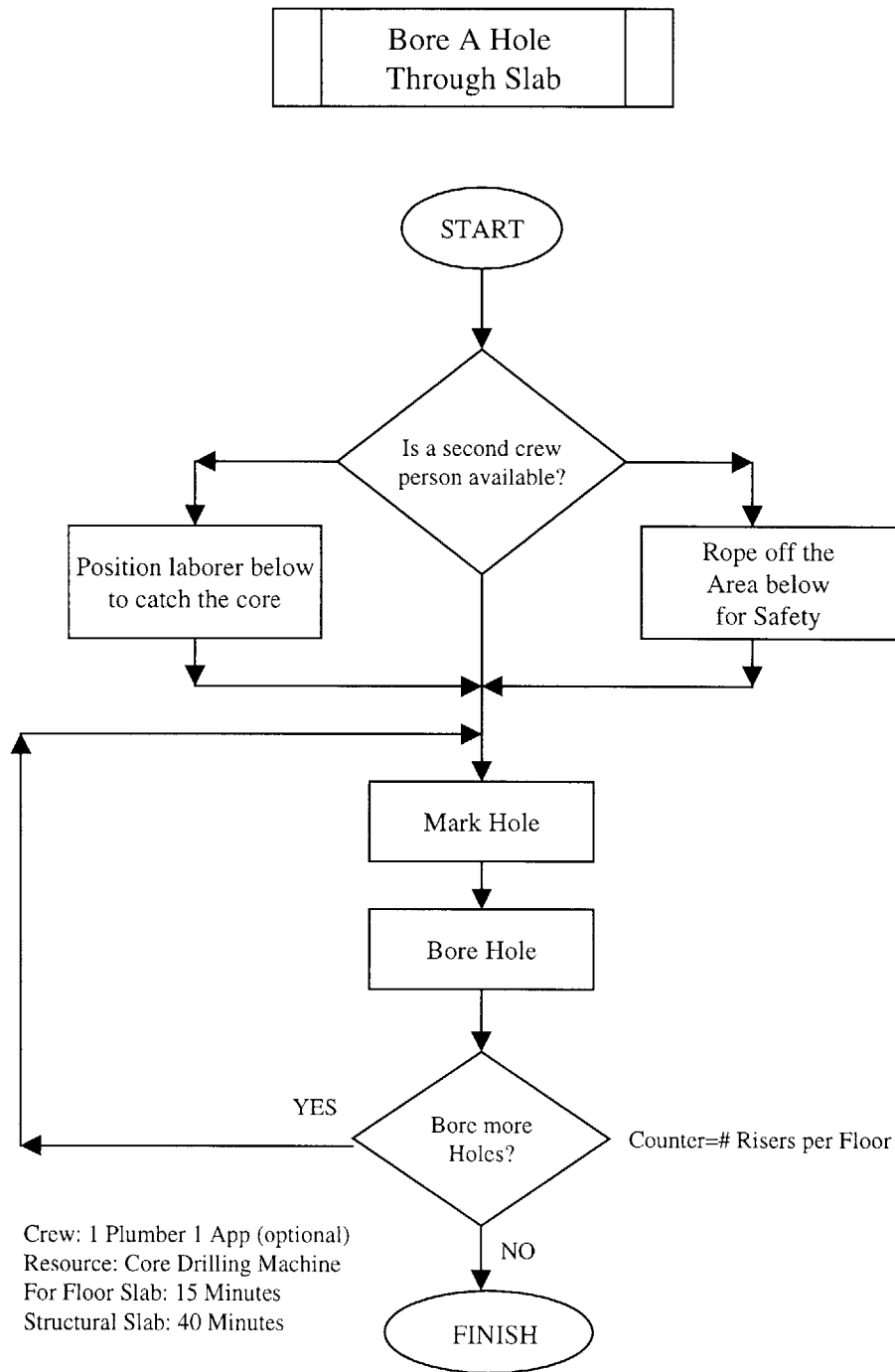
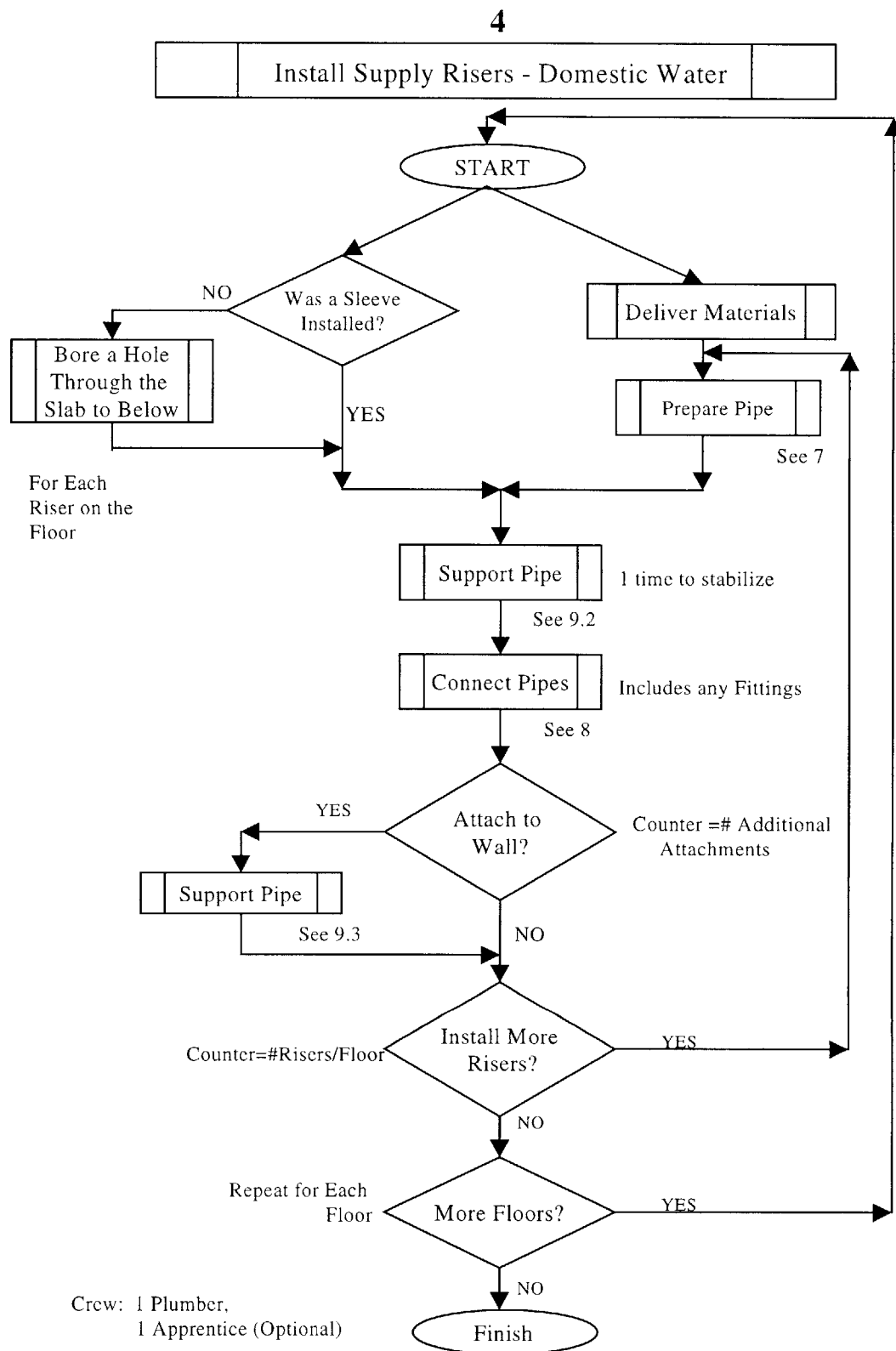


Figure A.11: Install DWV Stacks

### 3.1



**Figure A.12: Bore A Hole Through A Slab**



**Figure A.13: Install Supply Risers**

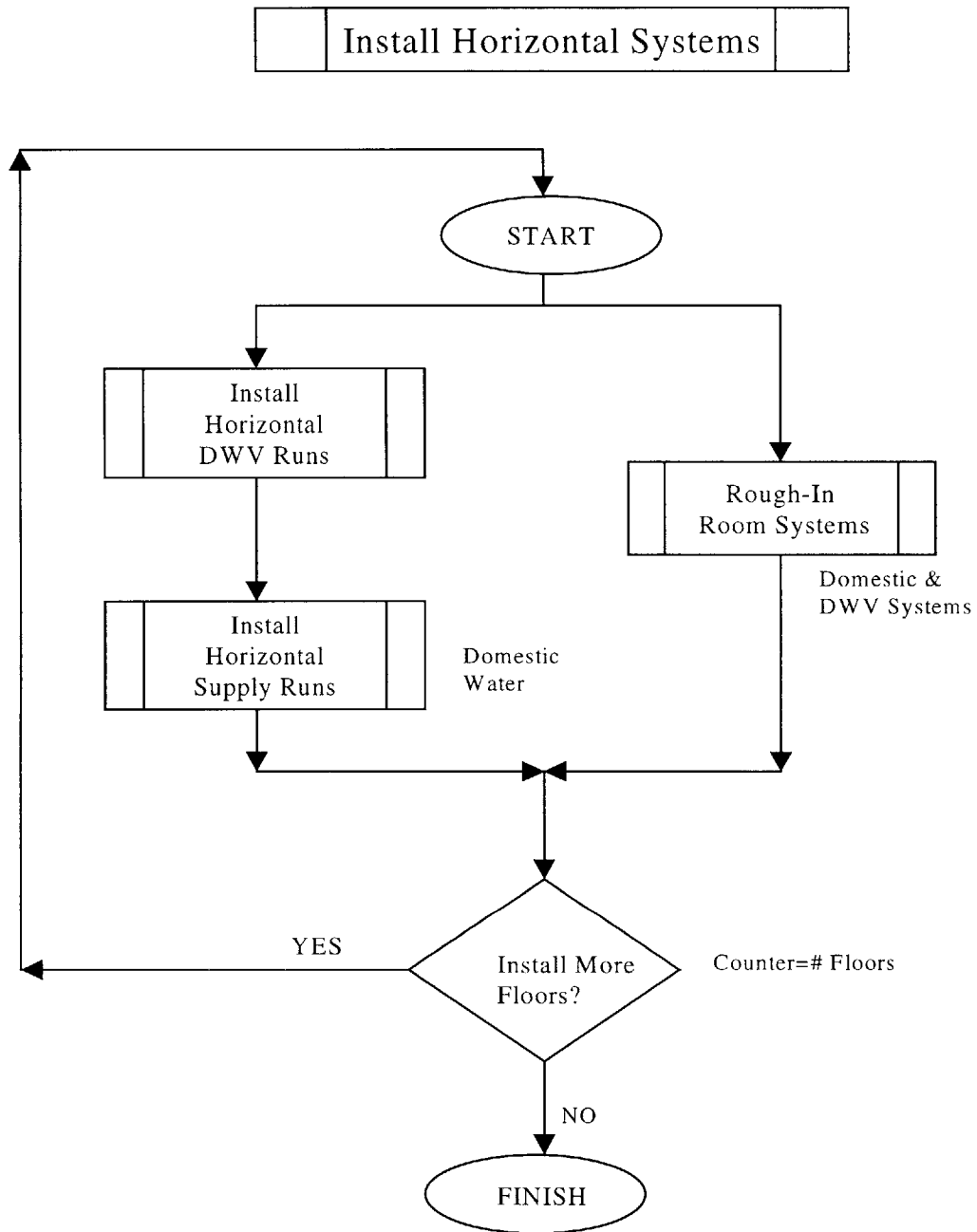
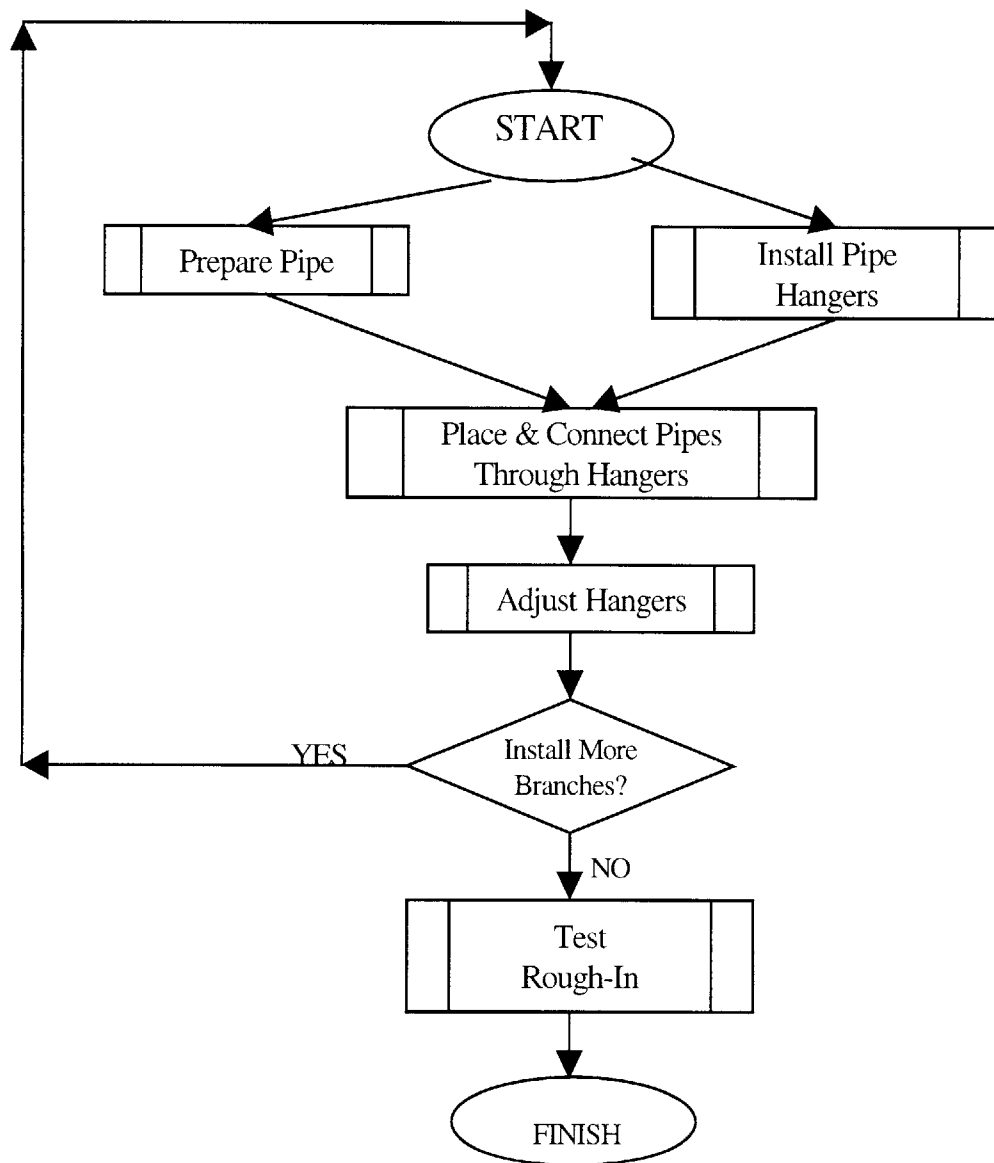
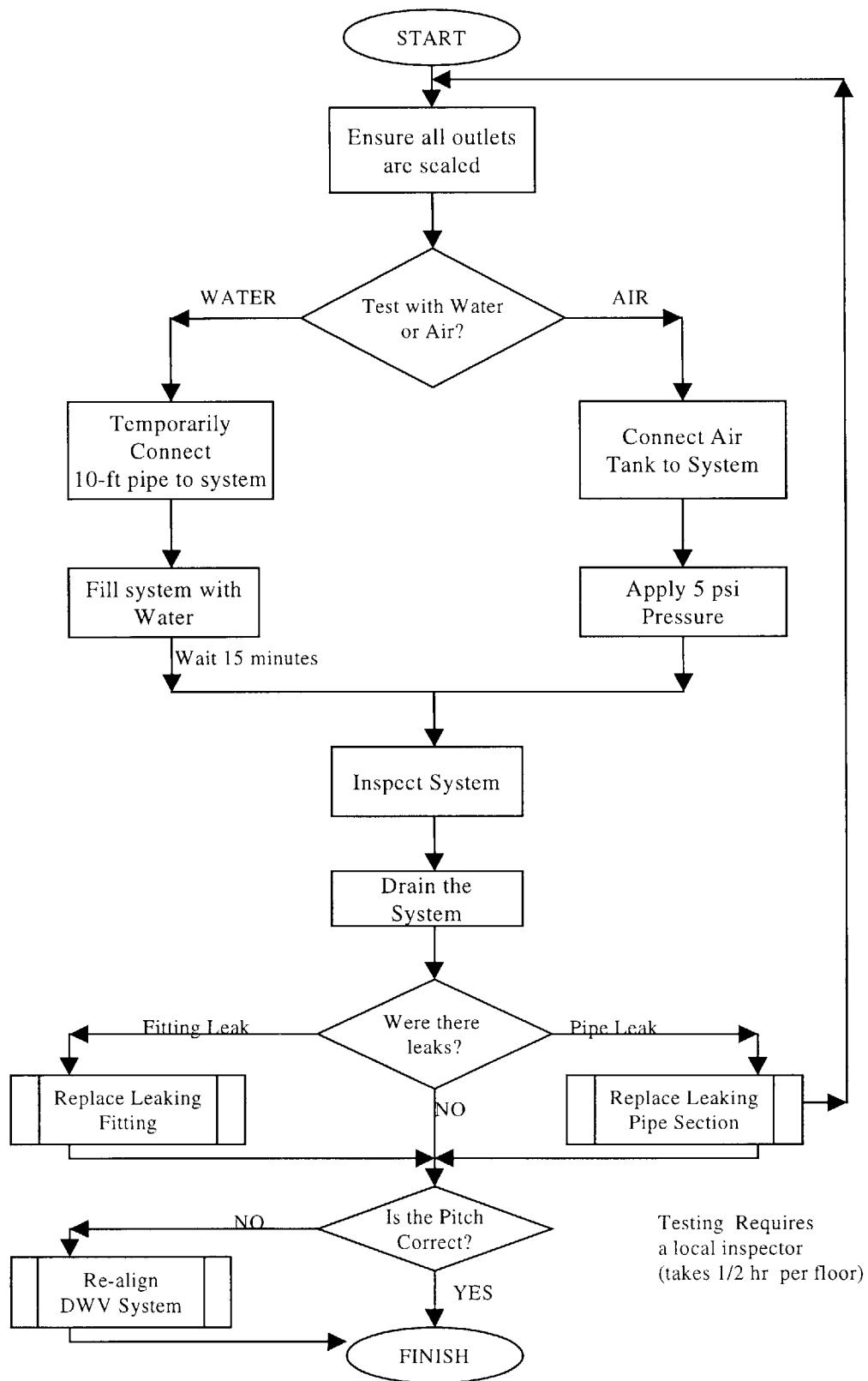


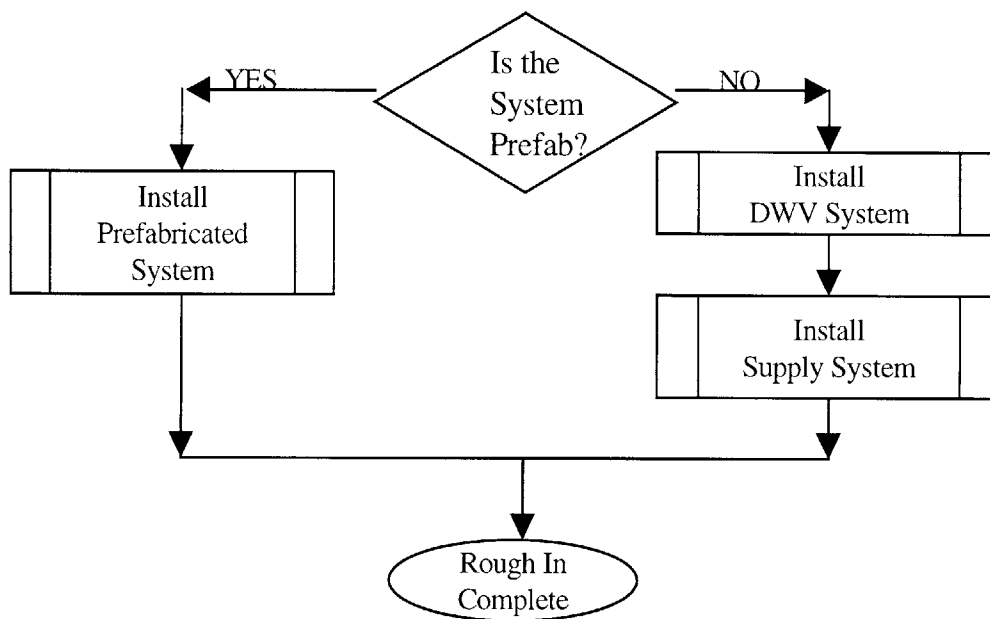
Figure A.14: Install Horizontal Systems



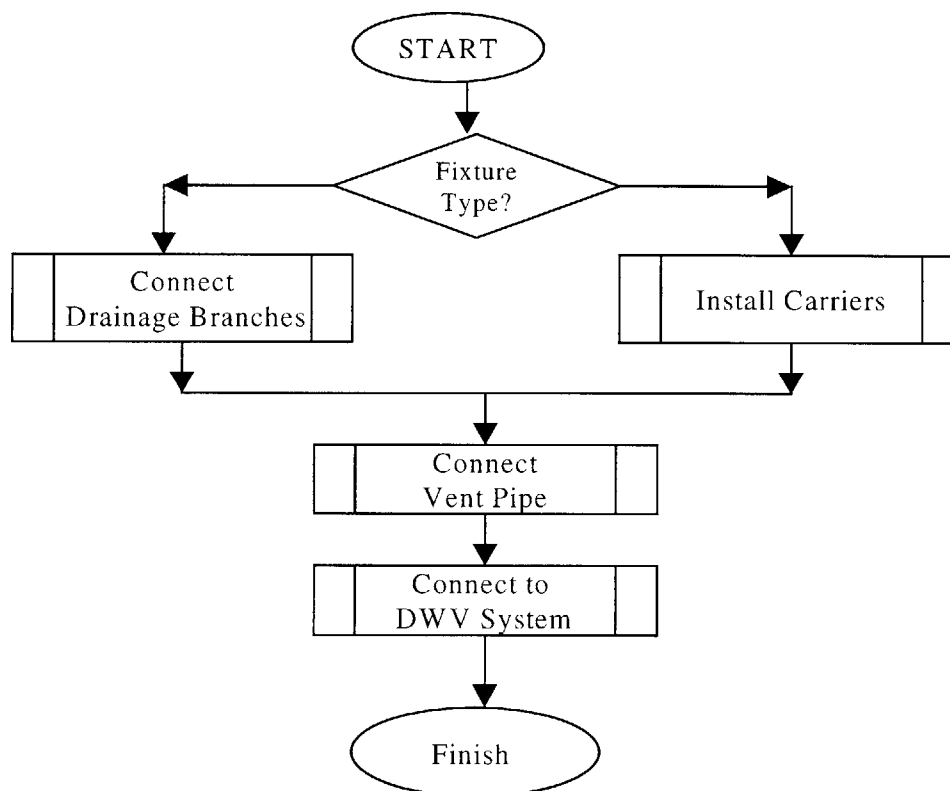
**Figure A.15: Install Horizontal DWV or Supply Runs**



**Figure A.16: Test DWV Rough-In**

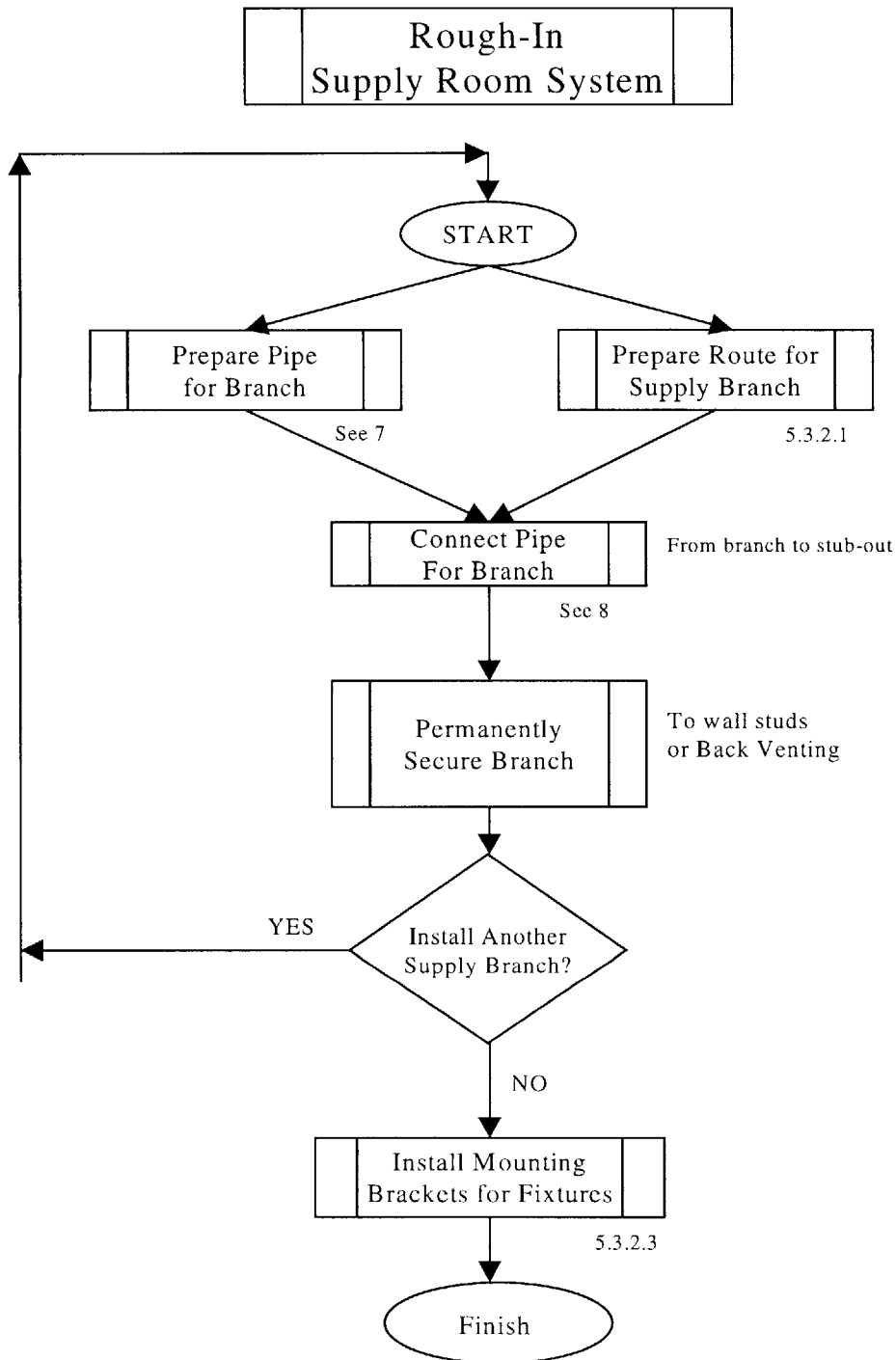


**Figure A.17: Rough-In Room Systems**



**Figure A.18: Install DWV System**

### 5.3.2



**Figure A.19: Rough-In Supply Piping for a Room System**



### 5.3.2.1

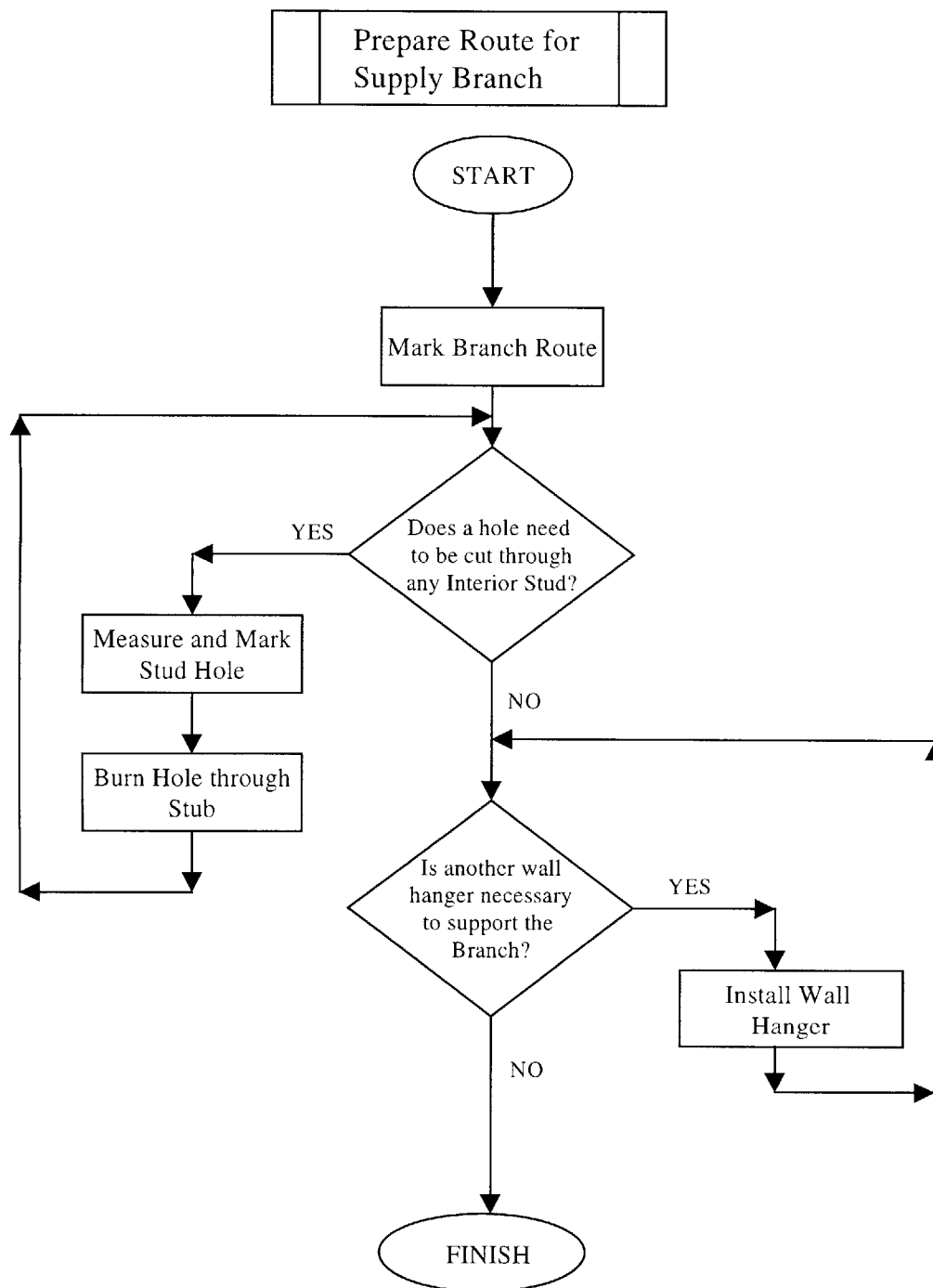
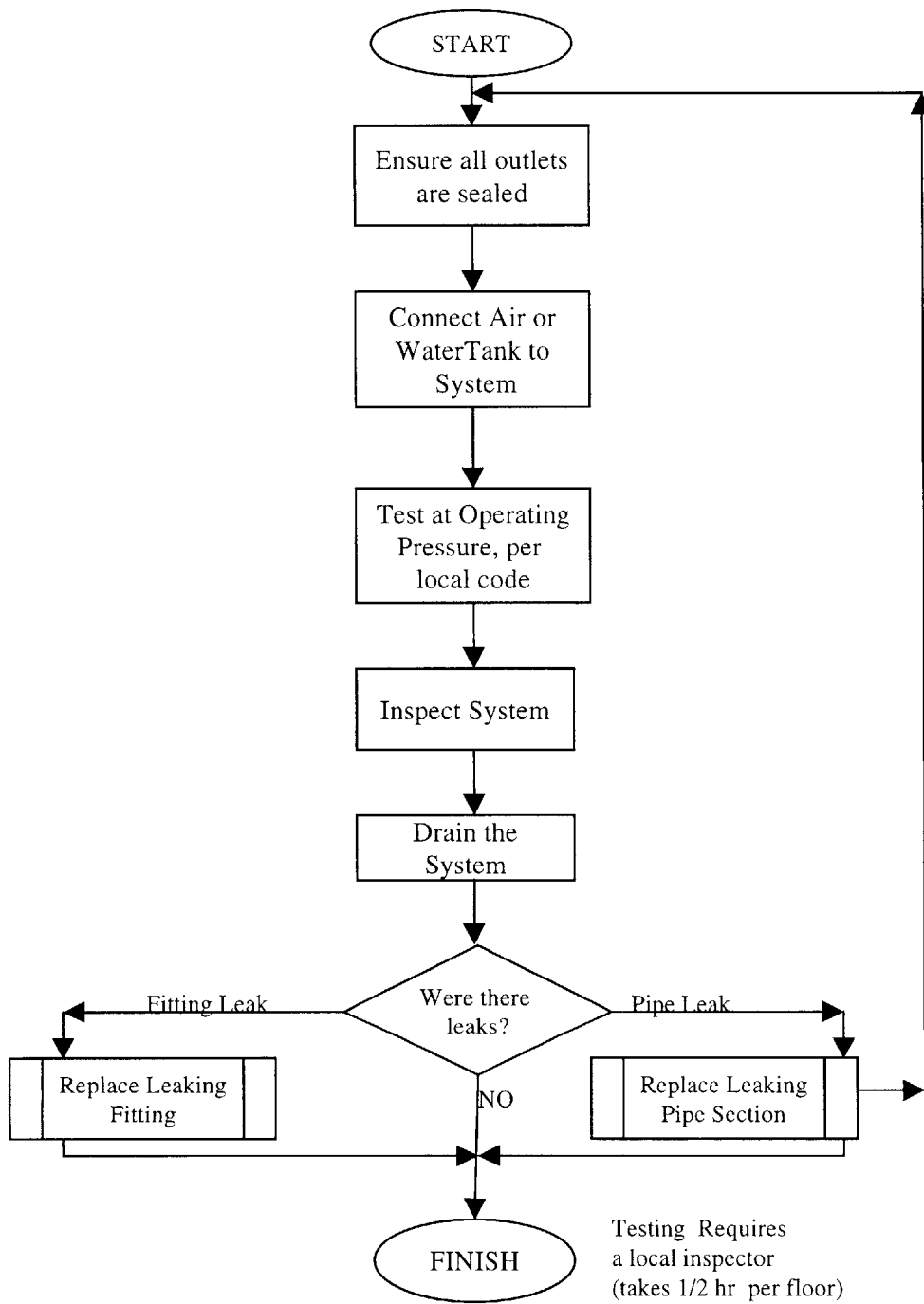
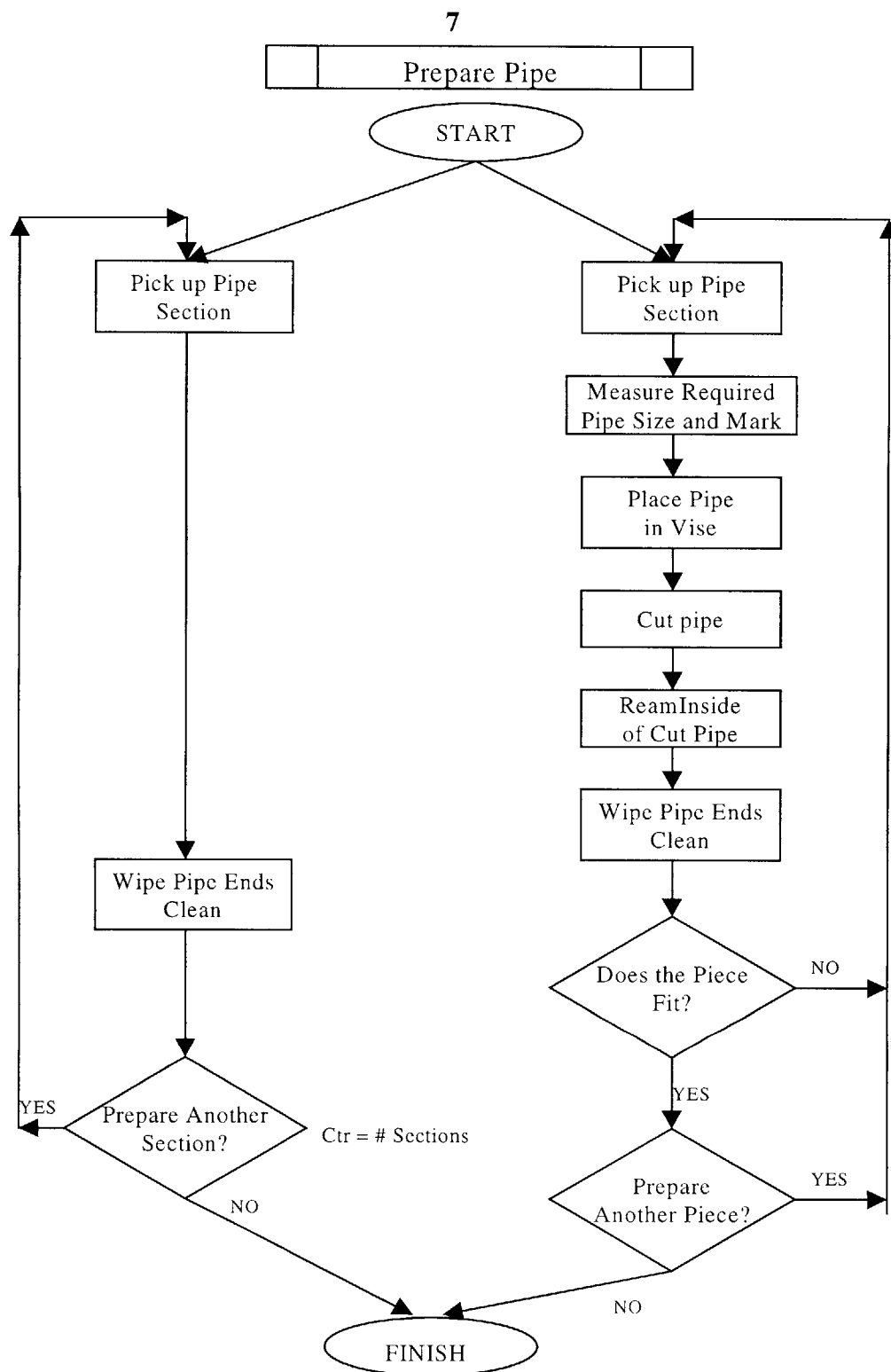


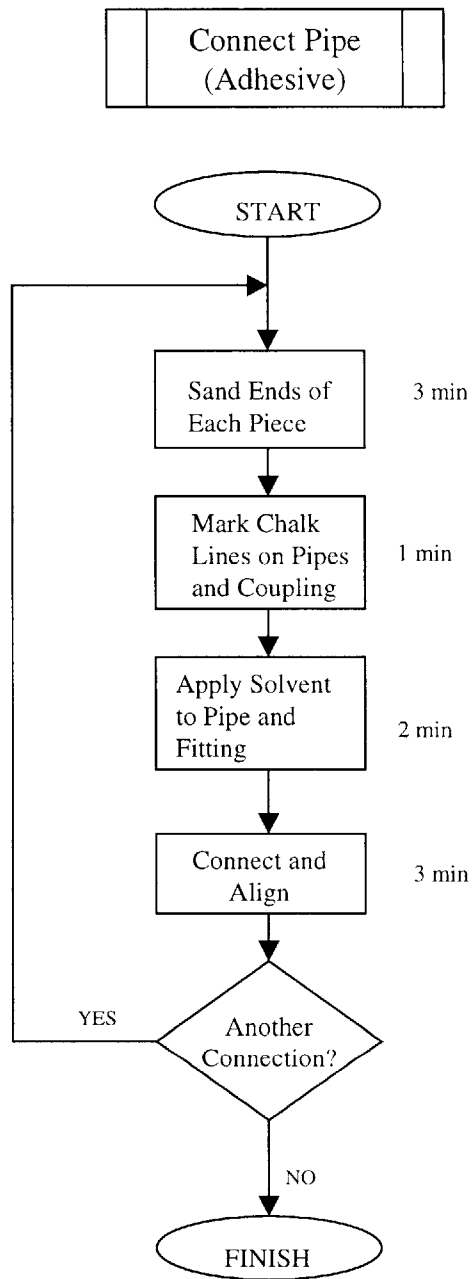
Figure A.20: Prepare Route for a Supply Branch



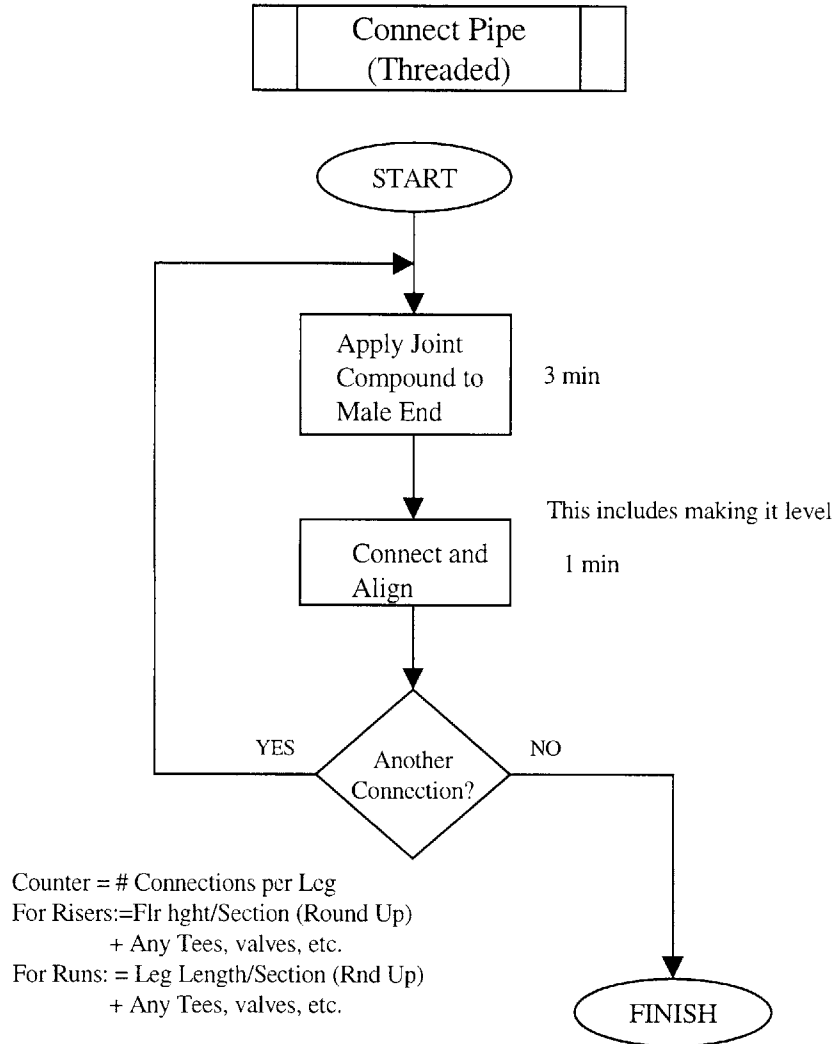
**Figure A.21: Test Supply Rough-In**



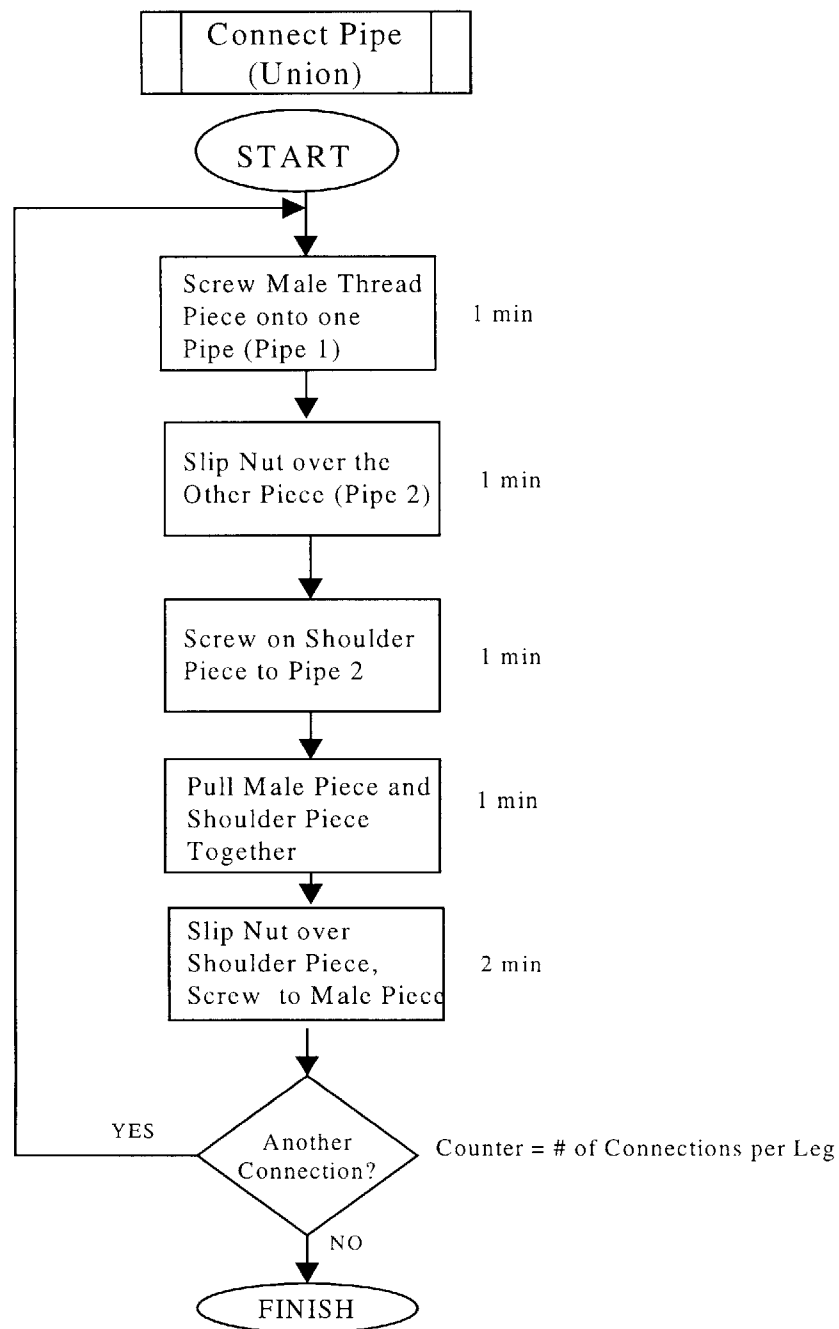
**Figure A.22: Prepare Pipe**



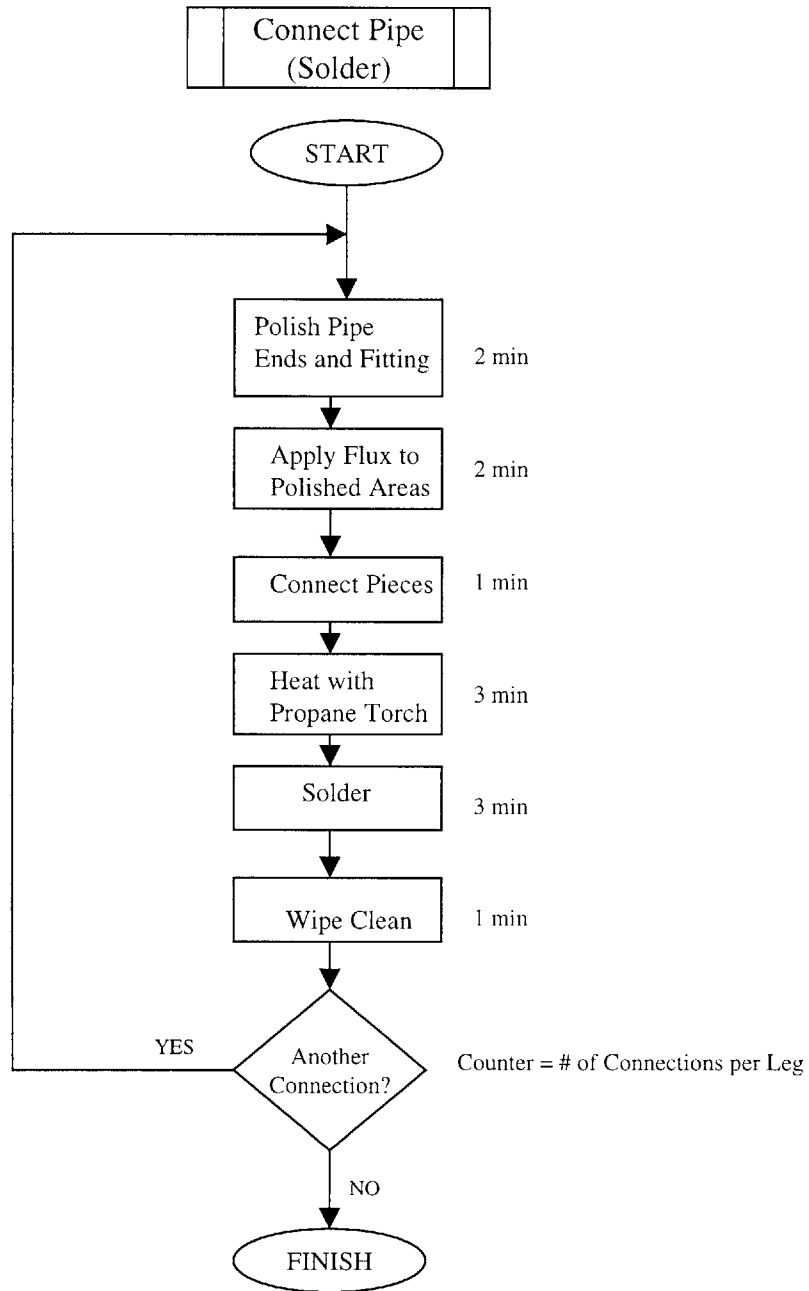
**Figure A.23: Connect Pipe (Adhesive)**



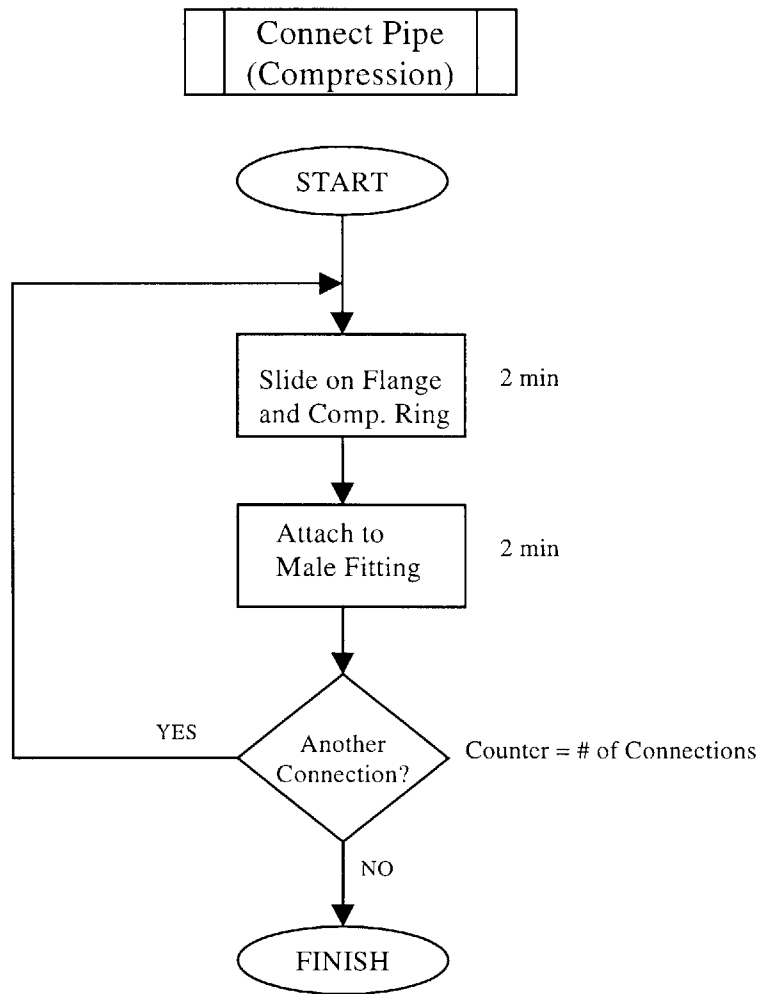
**Figure A.24: Connect Pipe (Threaded)**



**Figure A.25: Connect Pipe (Union Fittings)**

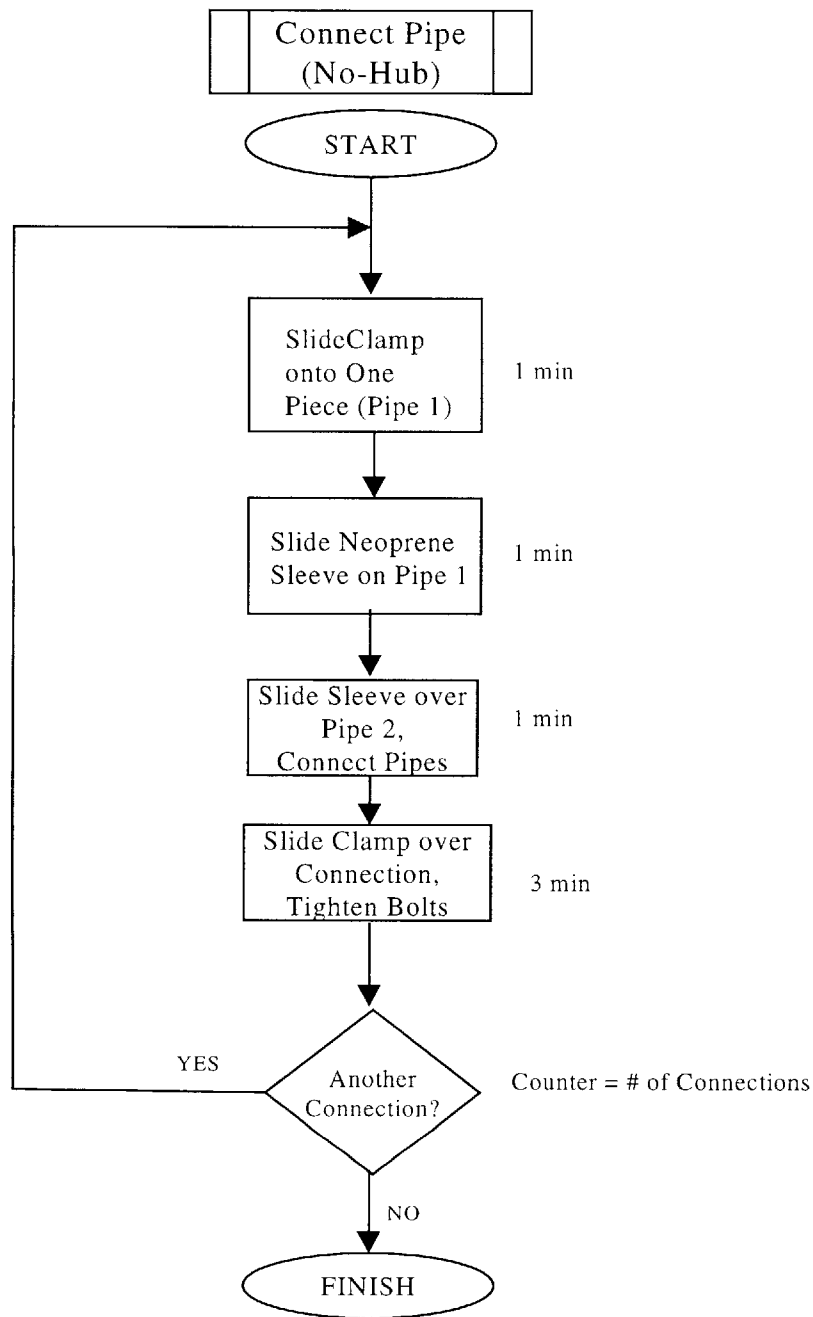


**Figure A.26: Connect Pipe (Soldered)**



**Figure A.27: Connect Pipe (Compression Fittings)**





**Figure A.28: Connect Pipe (No-Hub)**

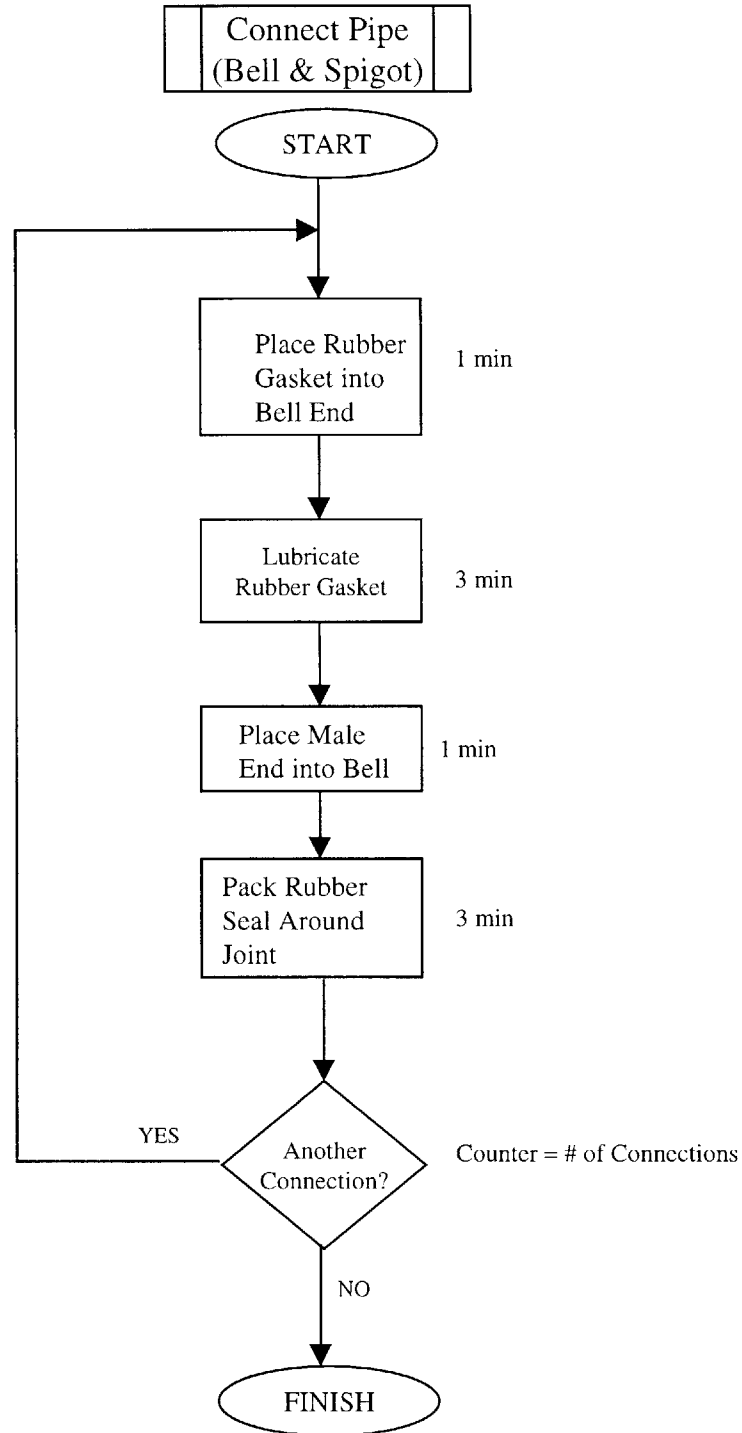
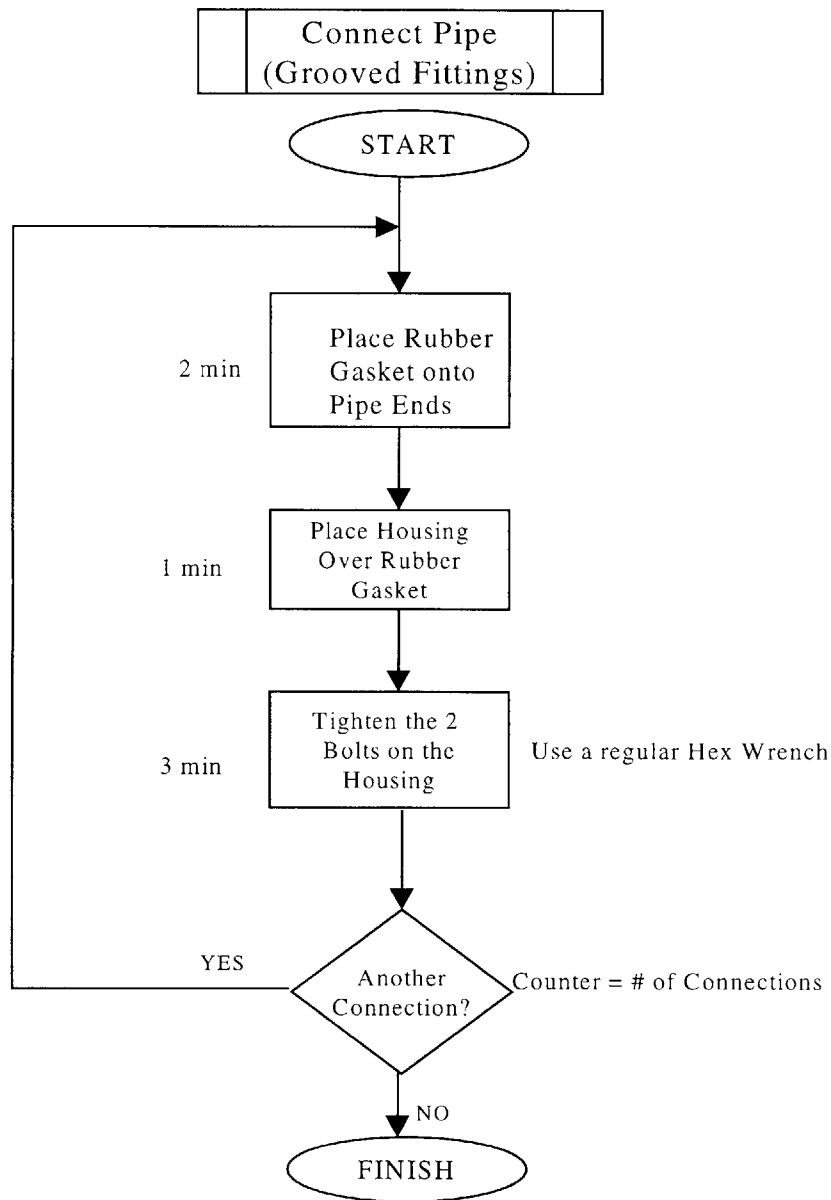
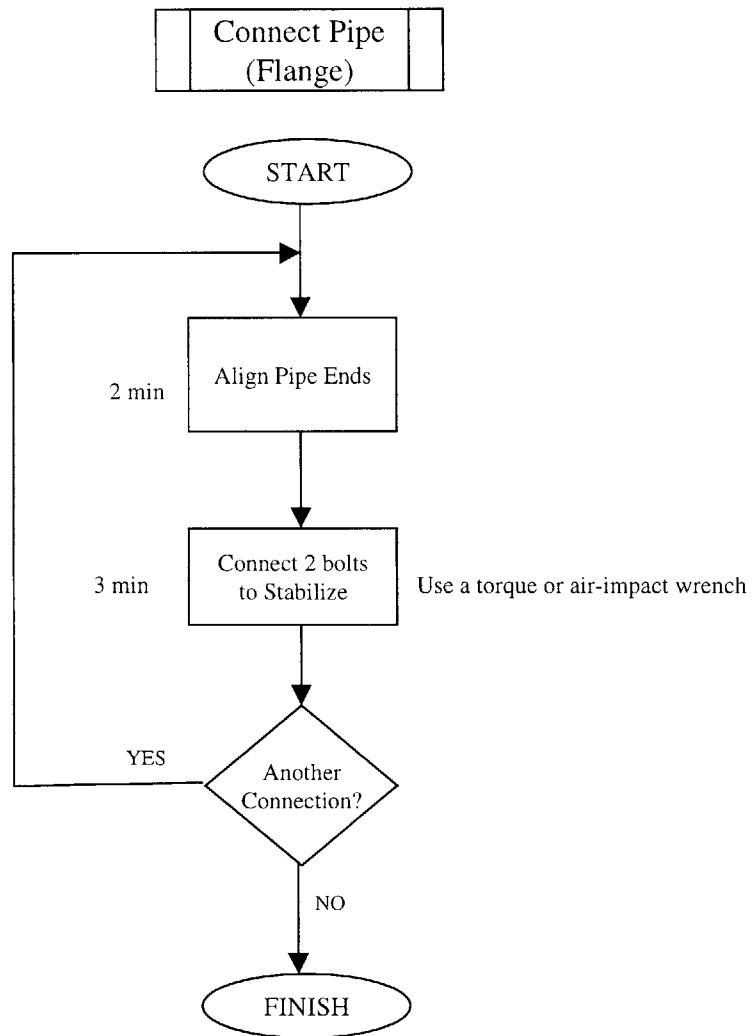


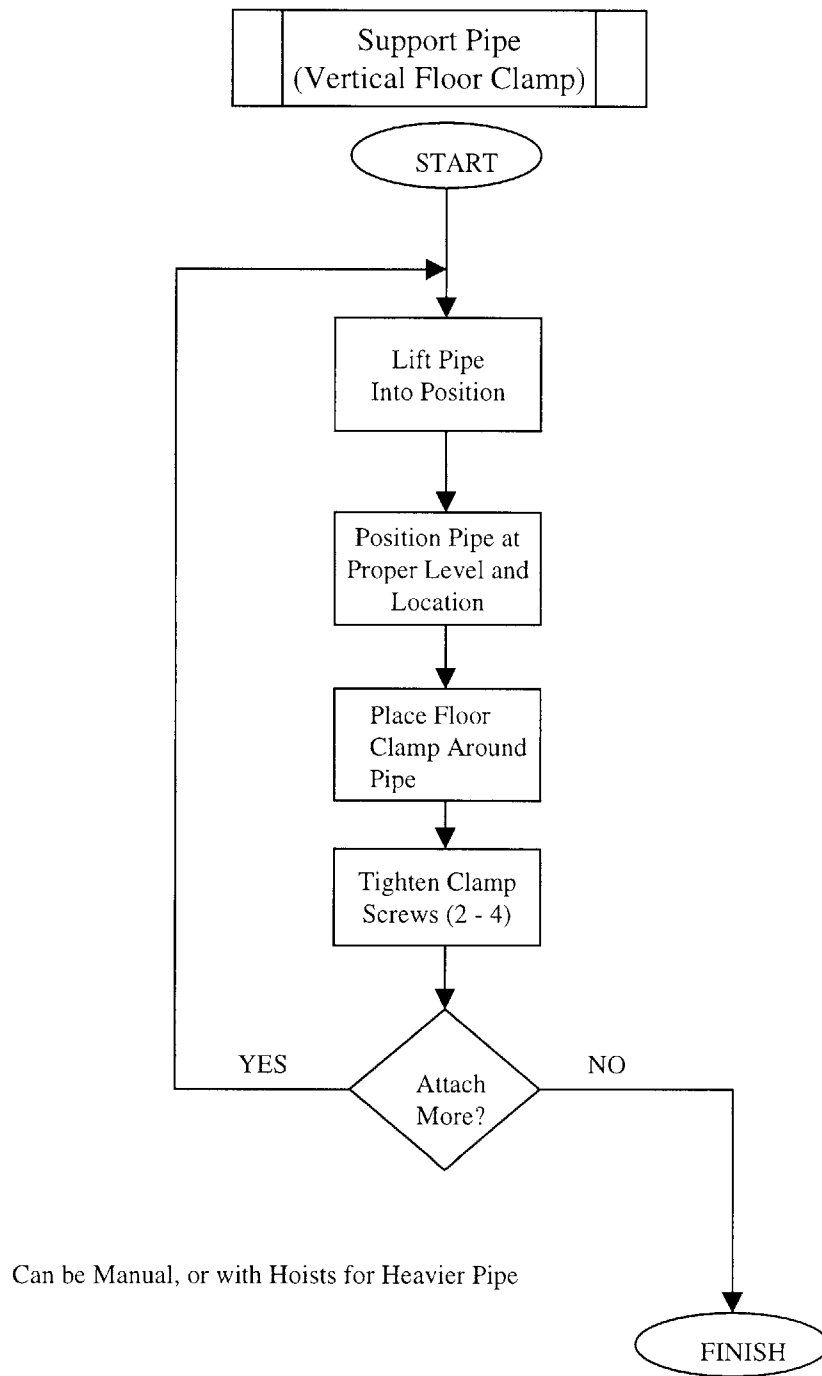
Figure A.29: Connect Pipe (Bell & Spigot)



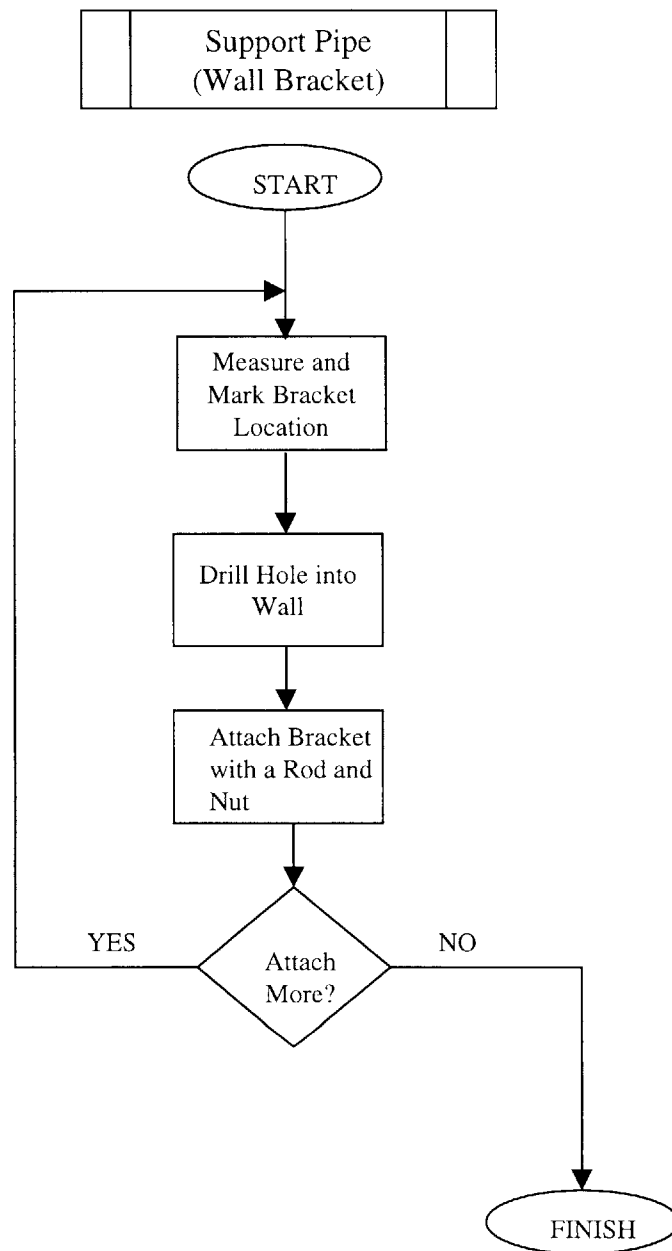
**Figure A.30: Connect Pipe (Grooved Fittings)**



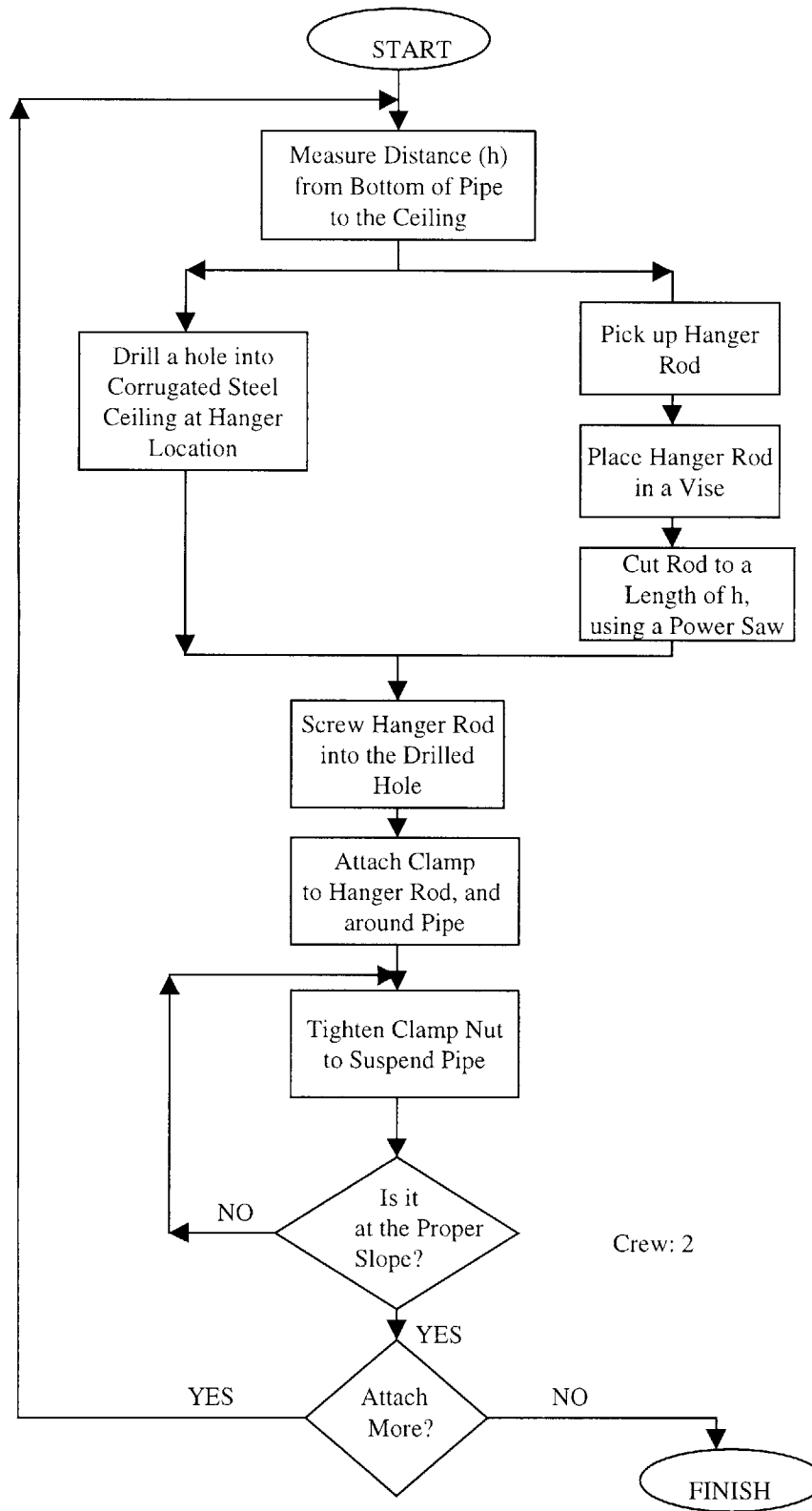
**Figure A.31: Connect Pipe (Flange)**



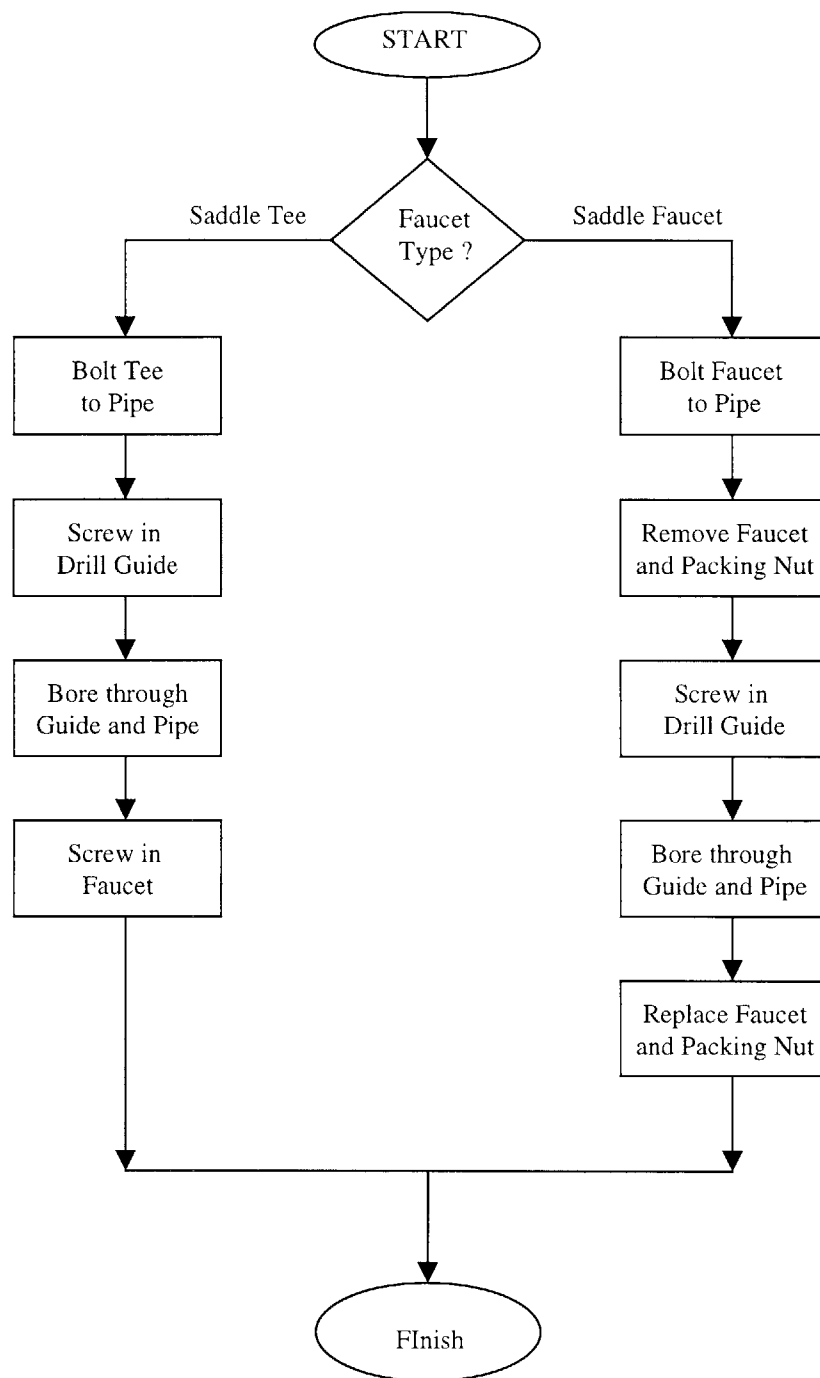
**Figure A.32: Support Pipe (Vertical Floor Clamp)**



**Figure A.33: Support Pipe (Wall Bracket)**



**Figure A.34: Support Pipe (Clevis Hanger)**



**Figure A.35: Install A Faucet**



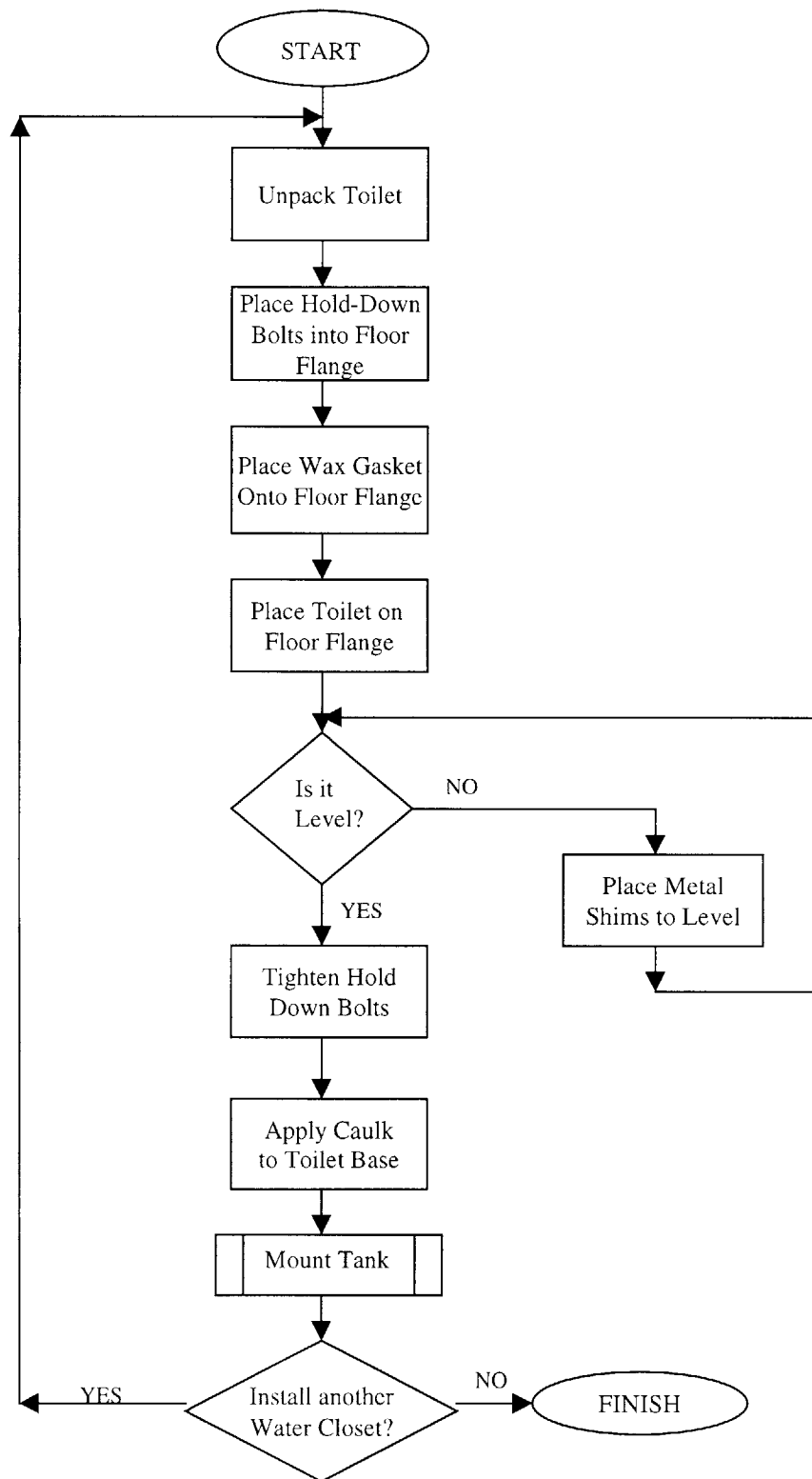
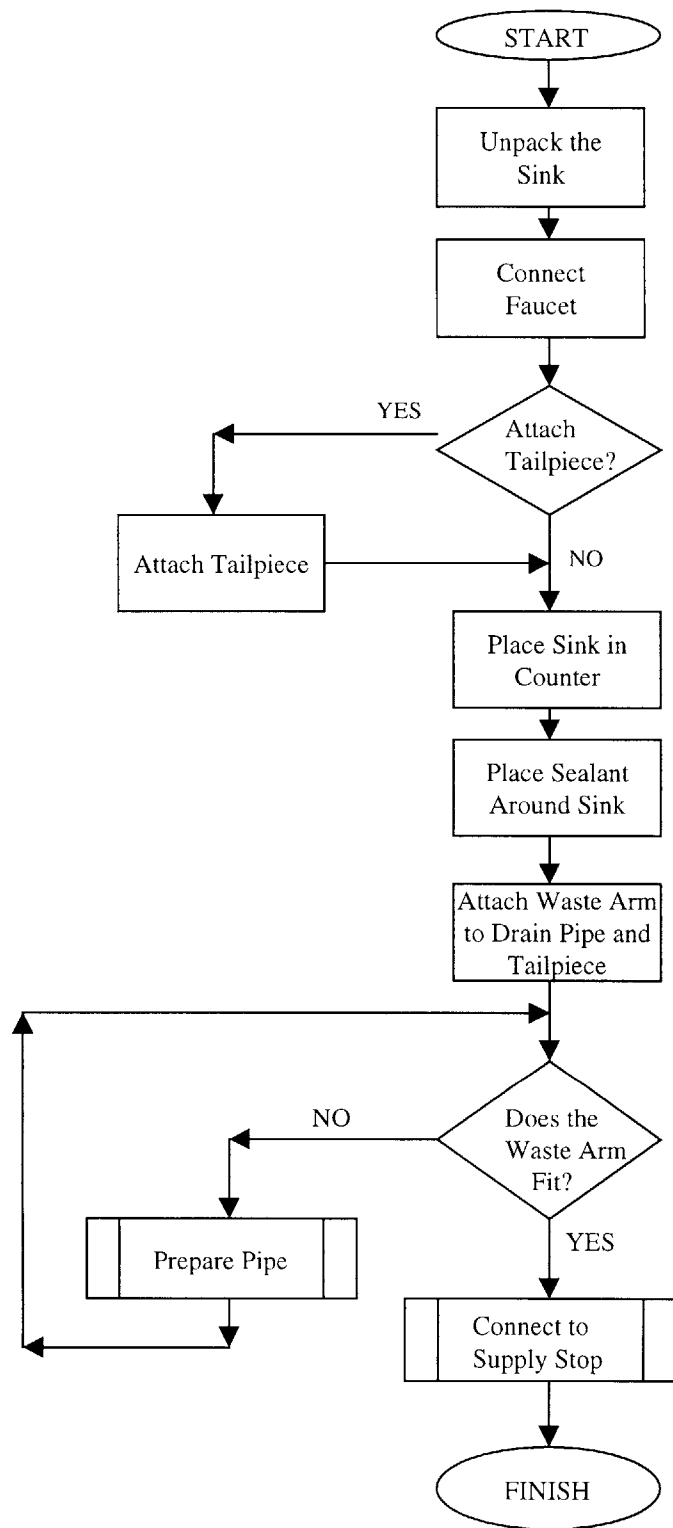
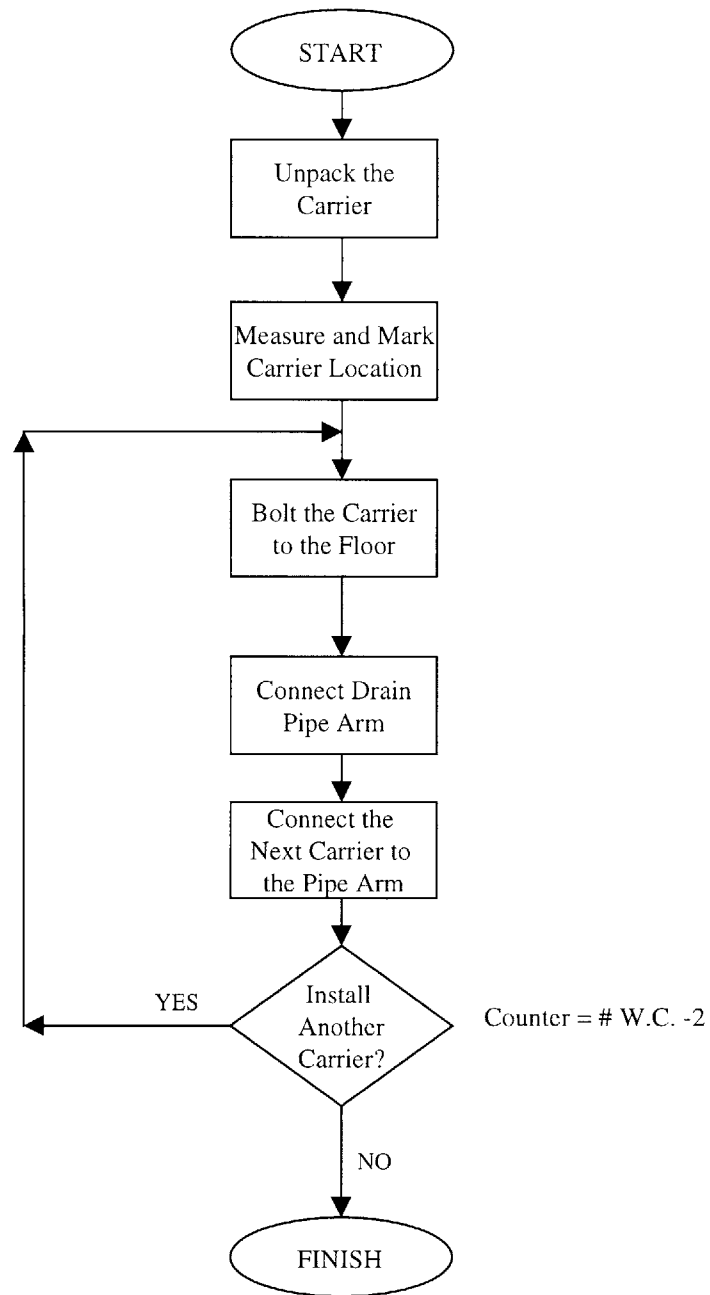


Figure A.36: Install A Water Closet



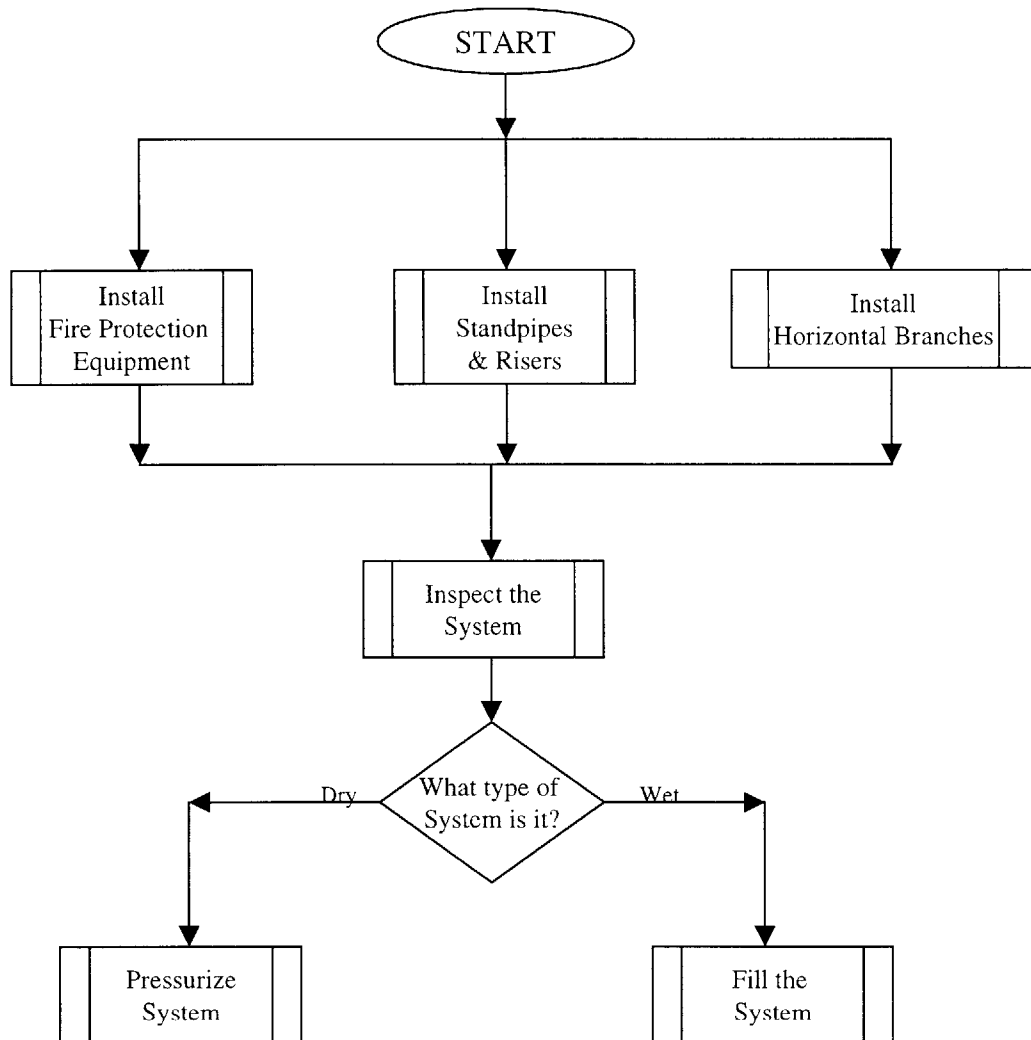
**Figure A.37: Install A Sink (Counter-Top)**



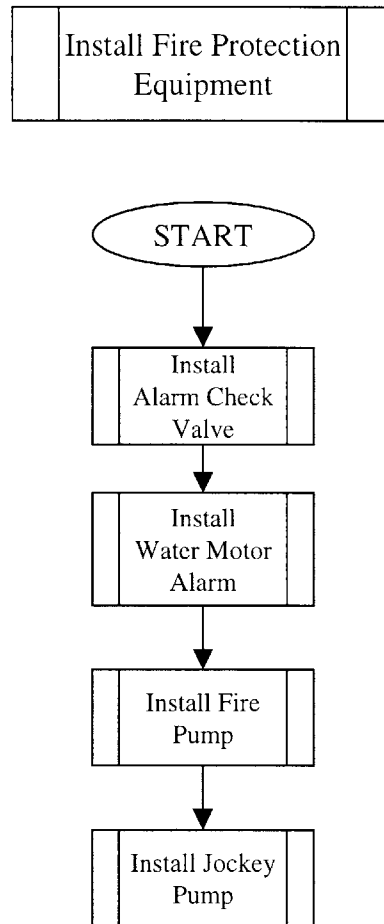
**Figure A.38: Install A Water Closet Carrier**



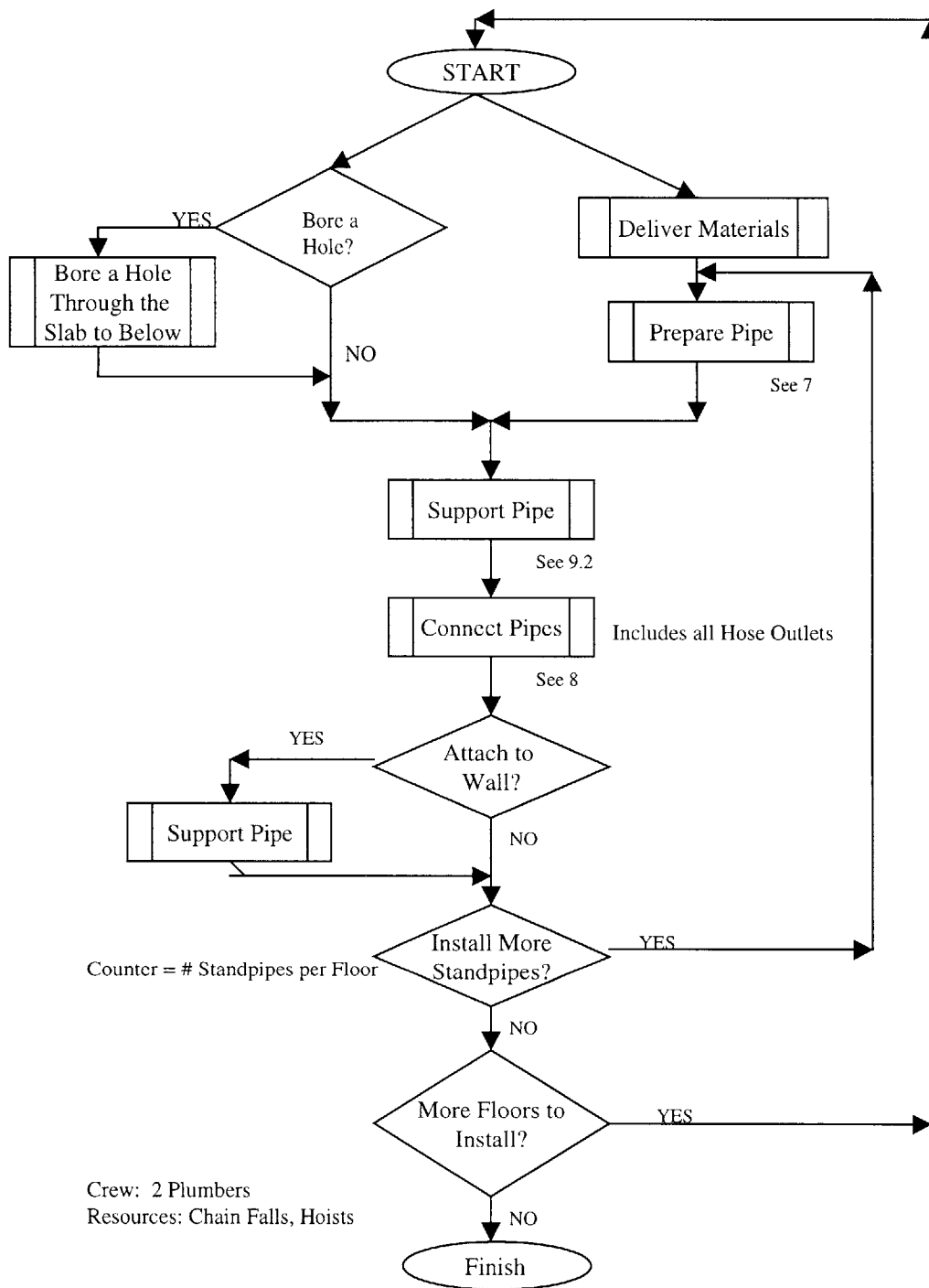
## **Appendix B: Process Flow Diagrams for Fire Protection Installation**



**Figure B.1: Overall Process for Fire Protection Installation**

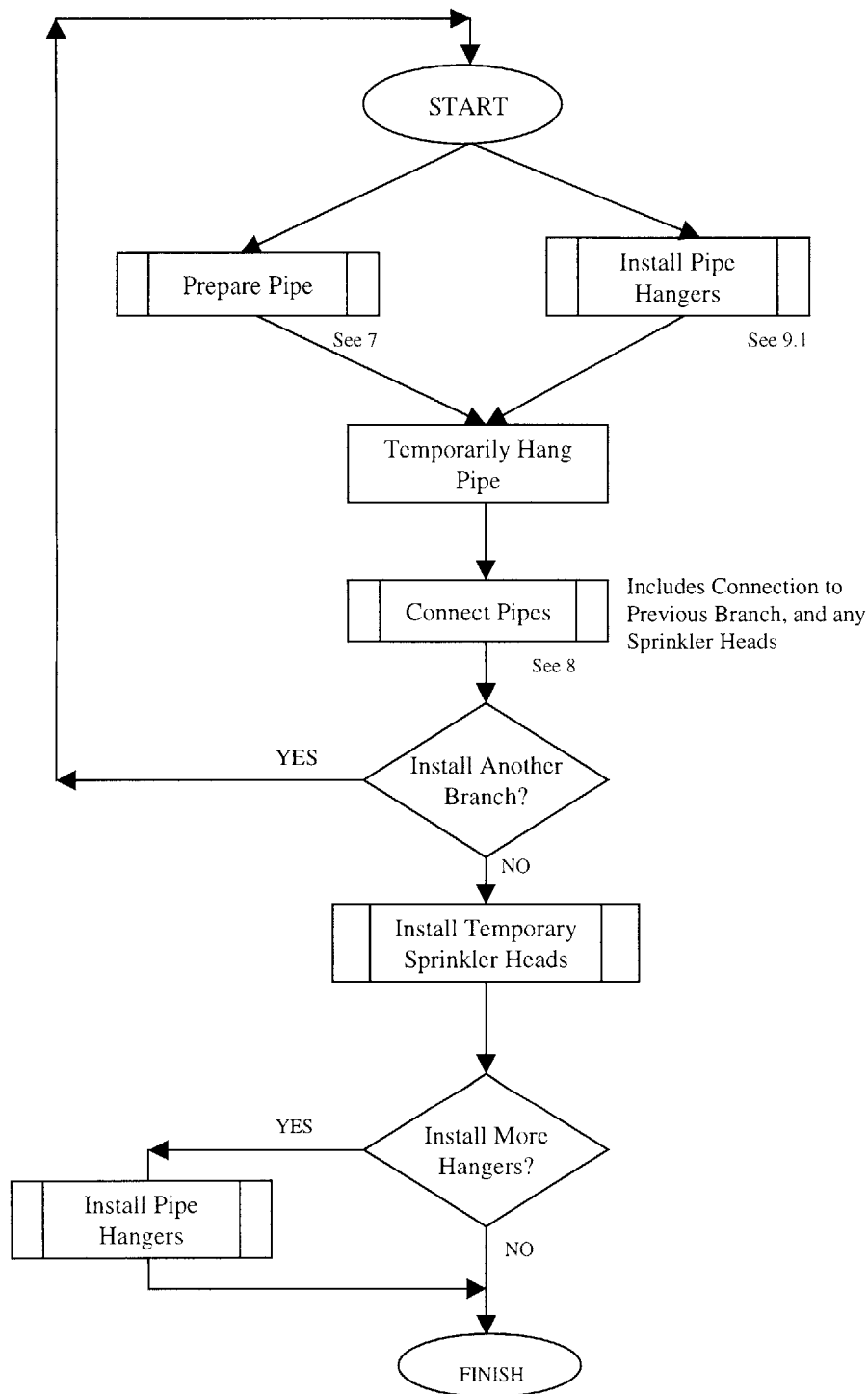


**Figure B.2: Install Fire Protection Equipment**

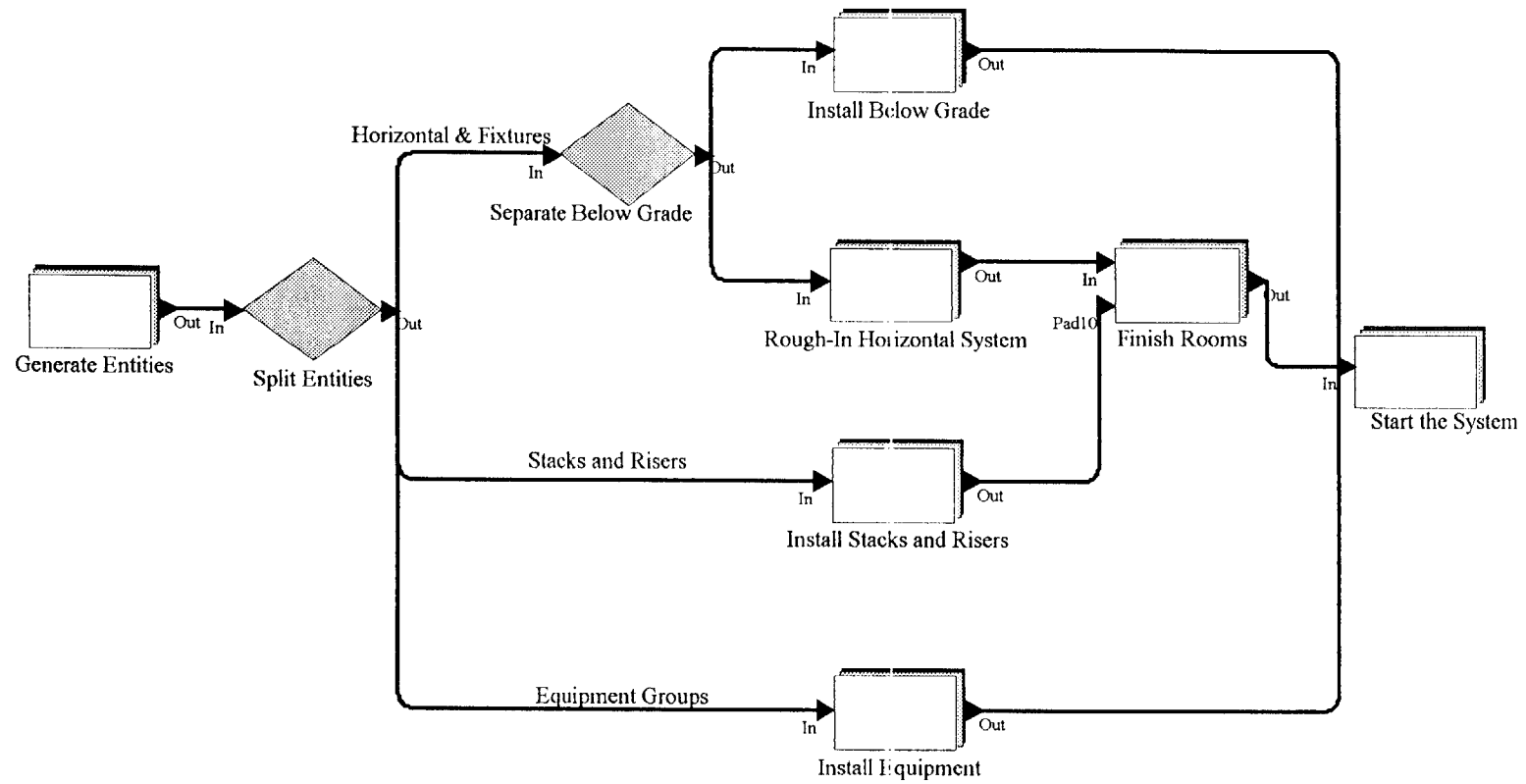


**Figure B.3: Install Standpipes and Risers**

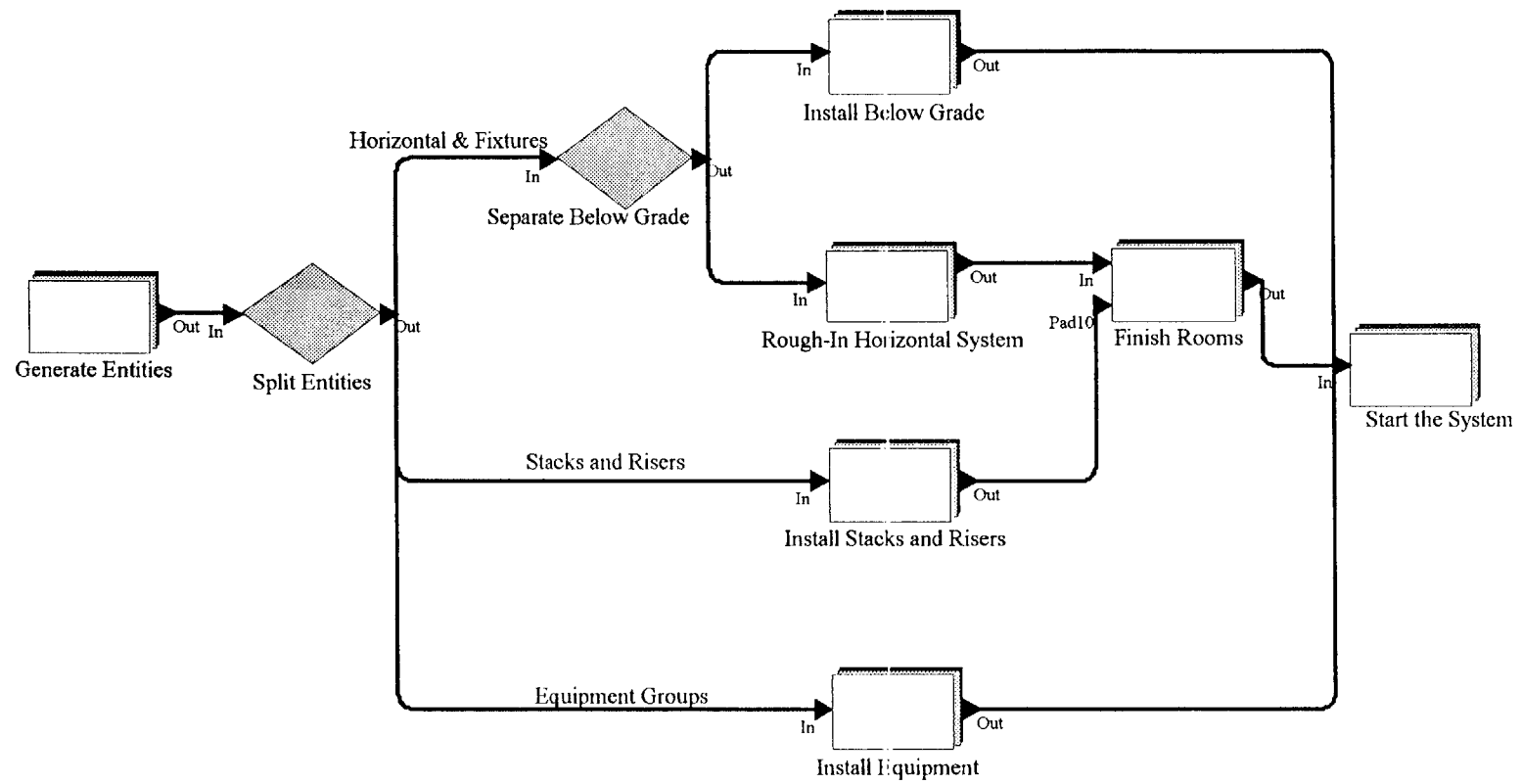




**Figure B.4: Install Horizontal Branches**



## **Appendix C: Computer-Based Plumbing Installation Model Layout**



**Figure C.1: Overall Process for Plumbing Installation**

# GENERATE ENTITIES

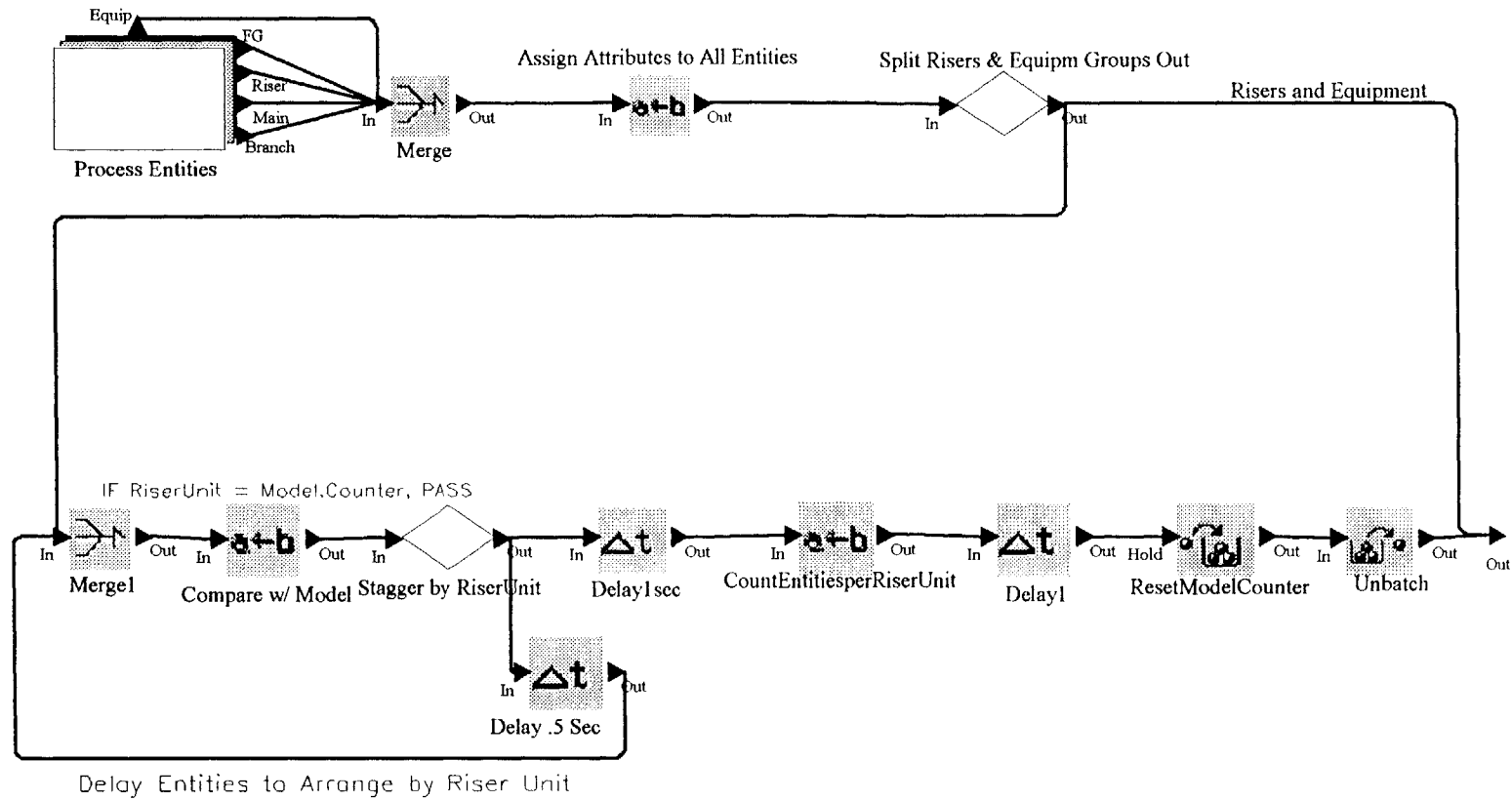


Figure C.2: Generate Entities

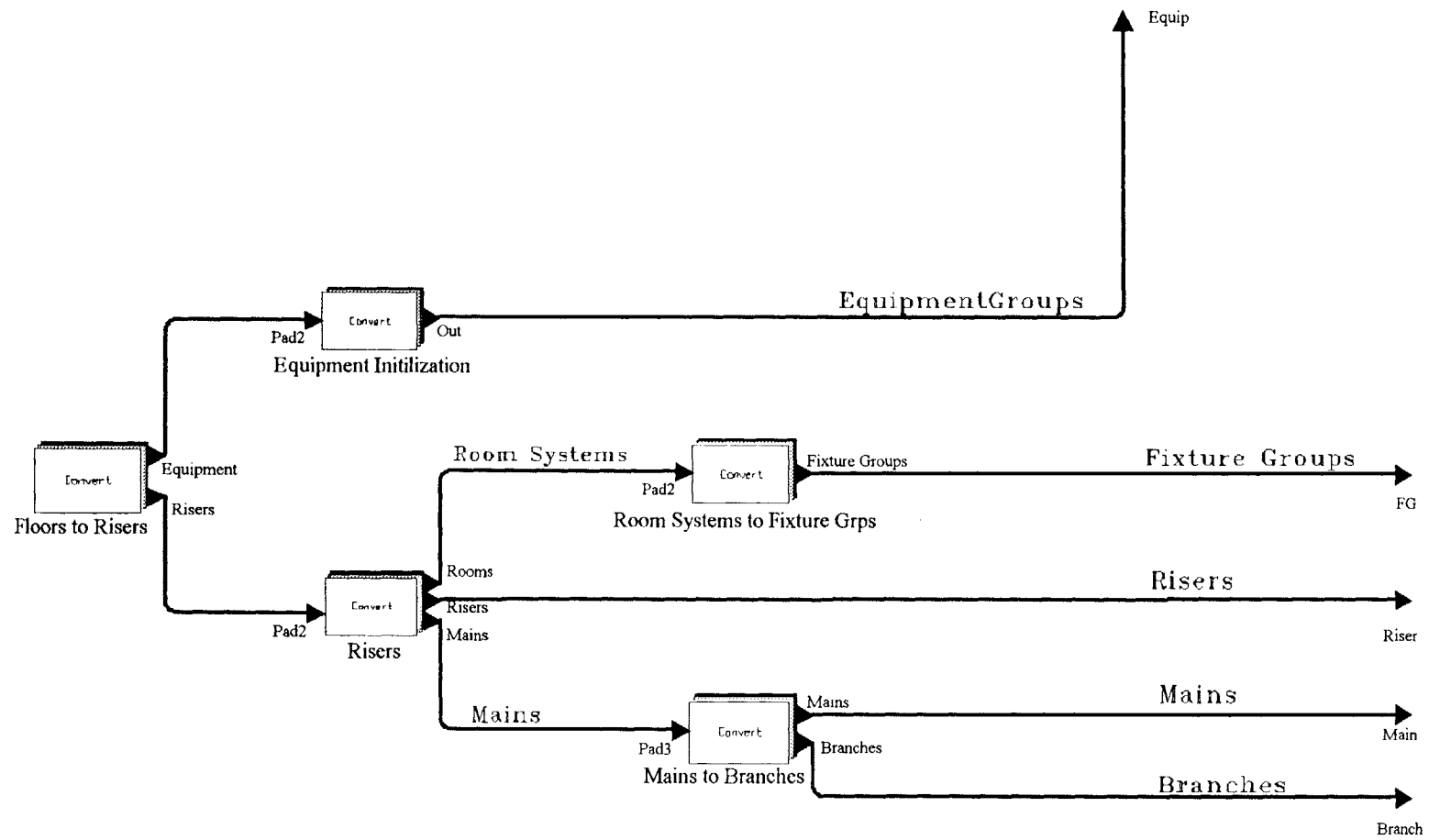
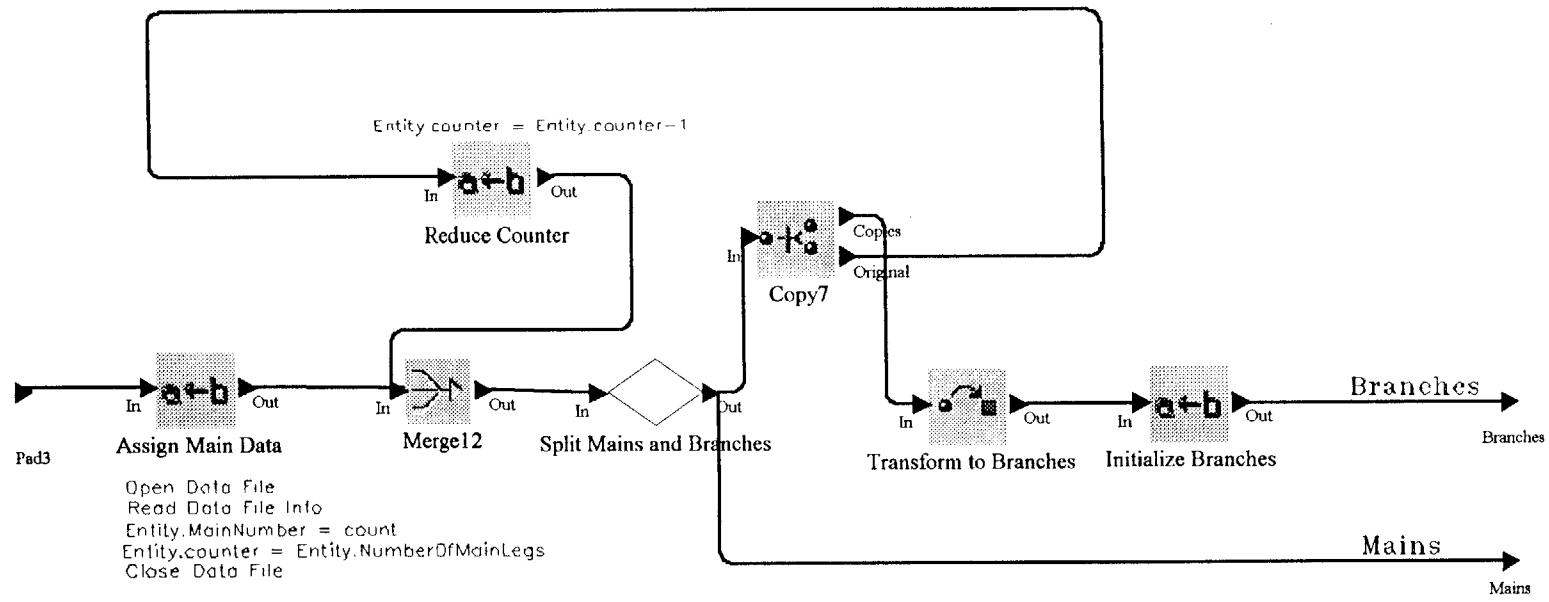


Figure C.3: Process/Generate Entities



## Mains To Branches

Figure C.4: Generate Branch Entities from Main Entities

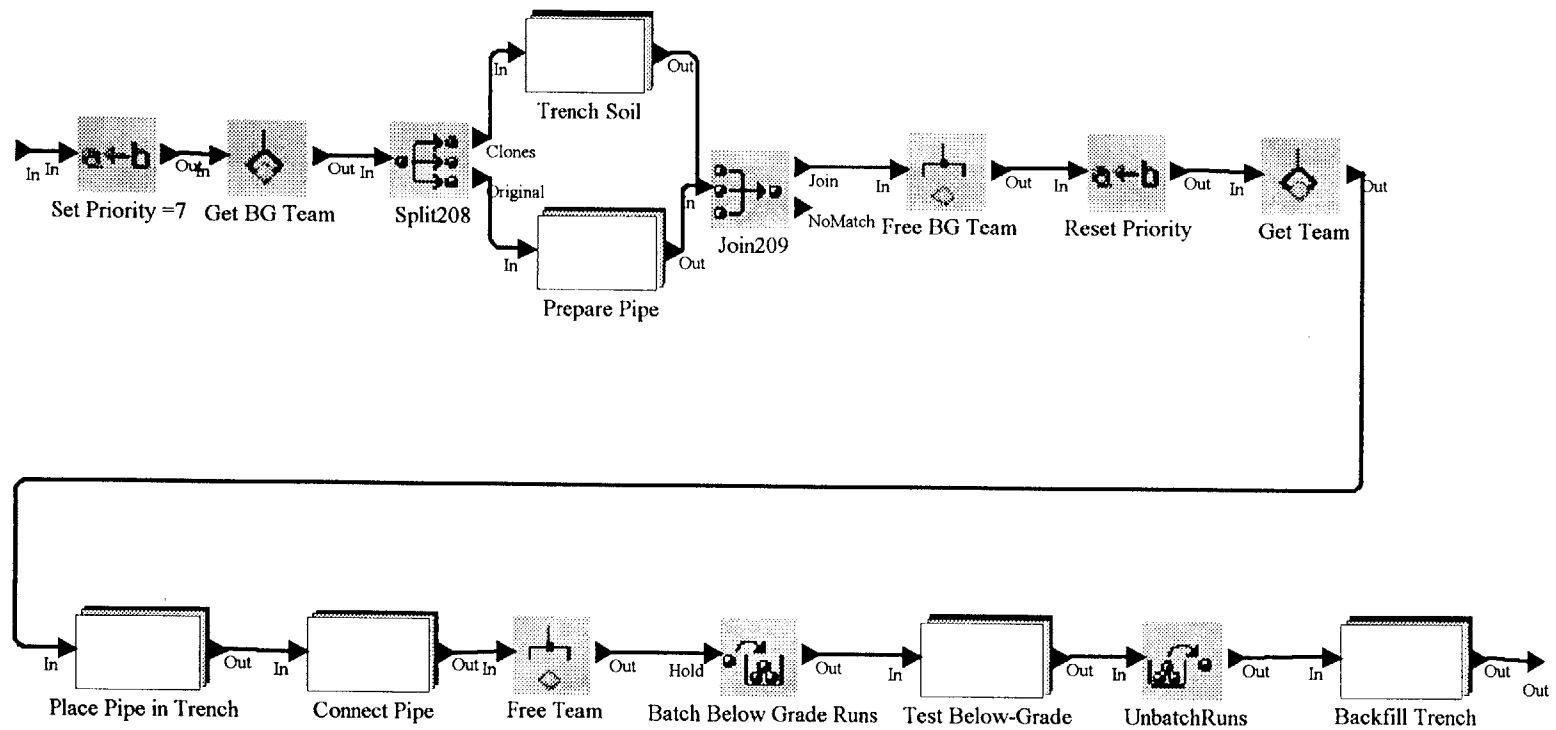


Figure C.5: Install Sub-Grade Piping



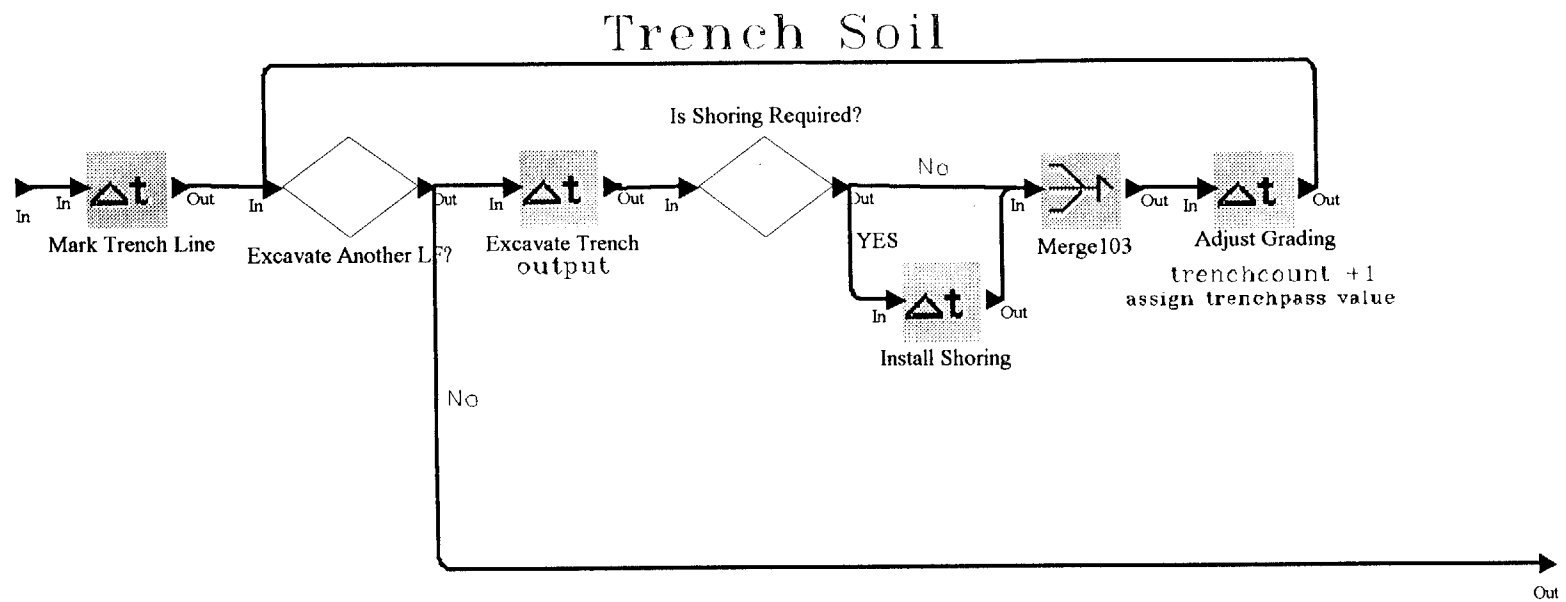
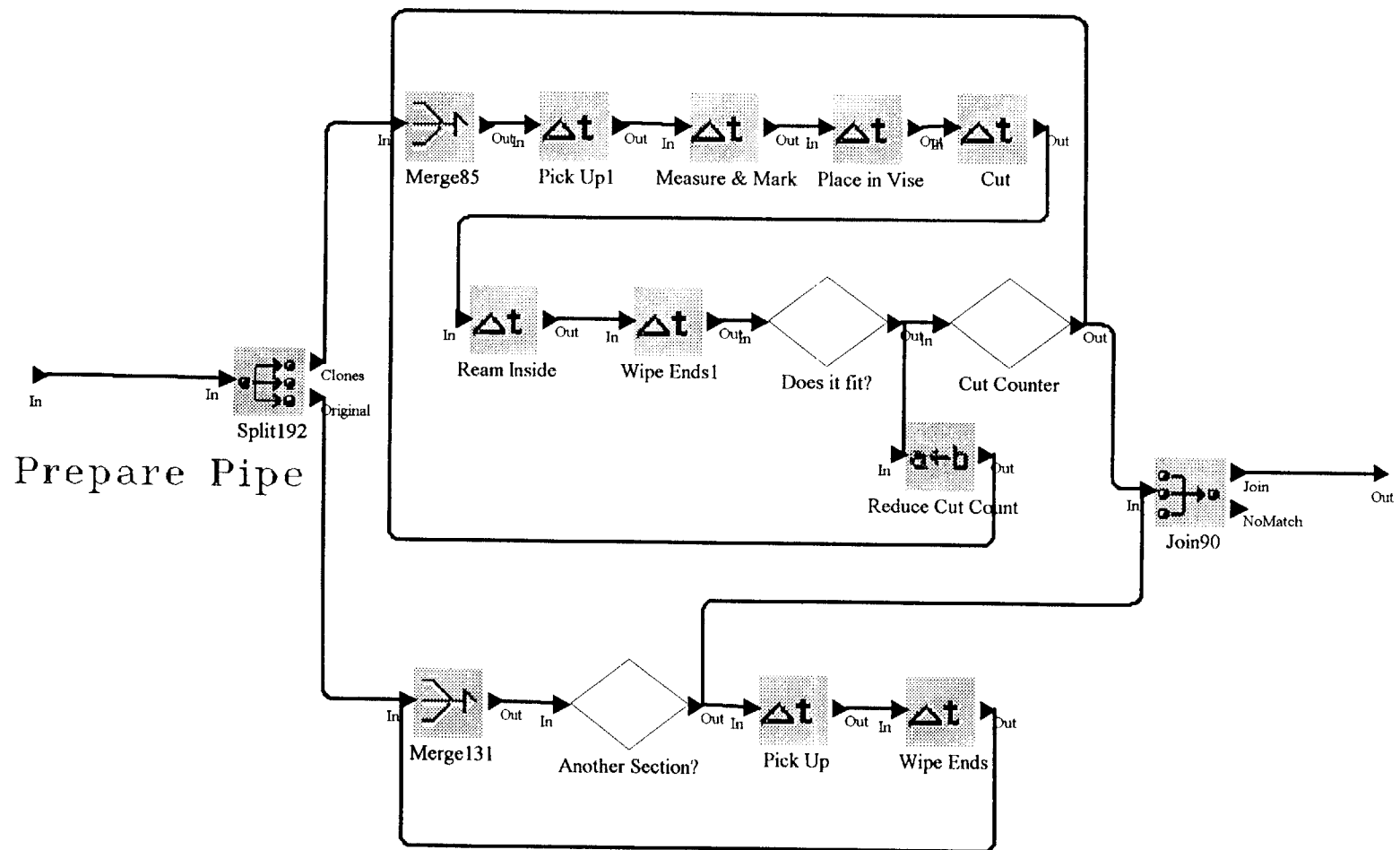


Figure C.6: Trench Soil



**Figure C.7: Prepare Pipe**

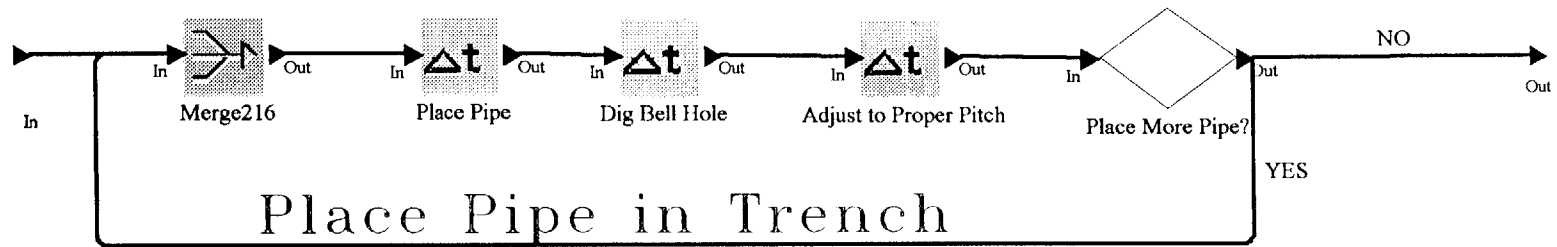
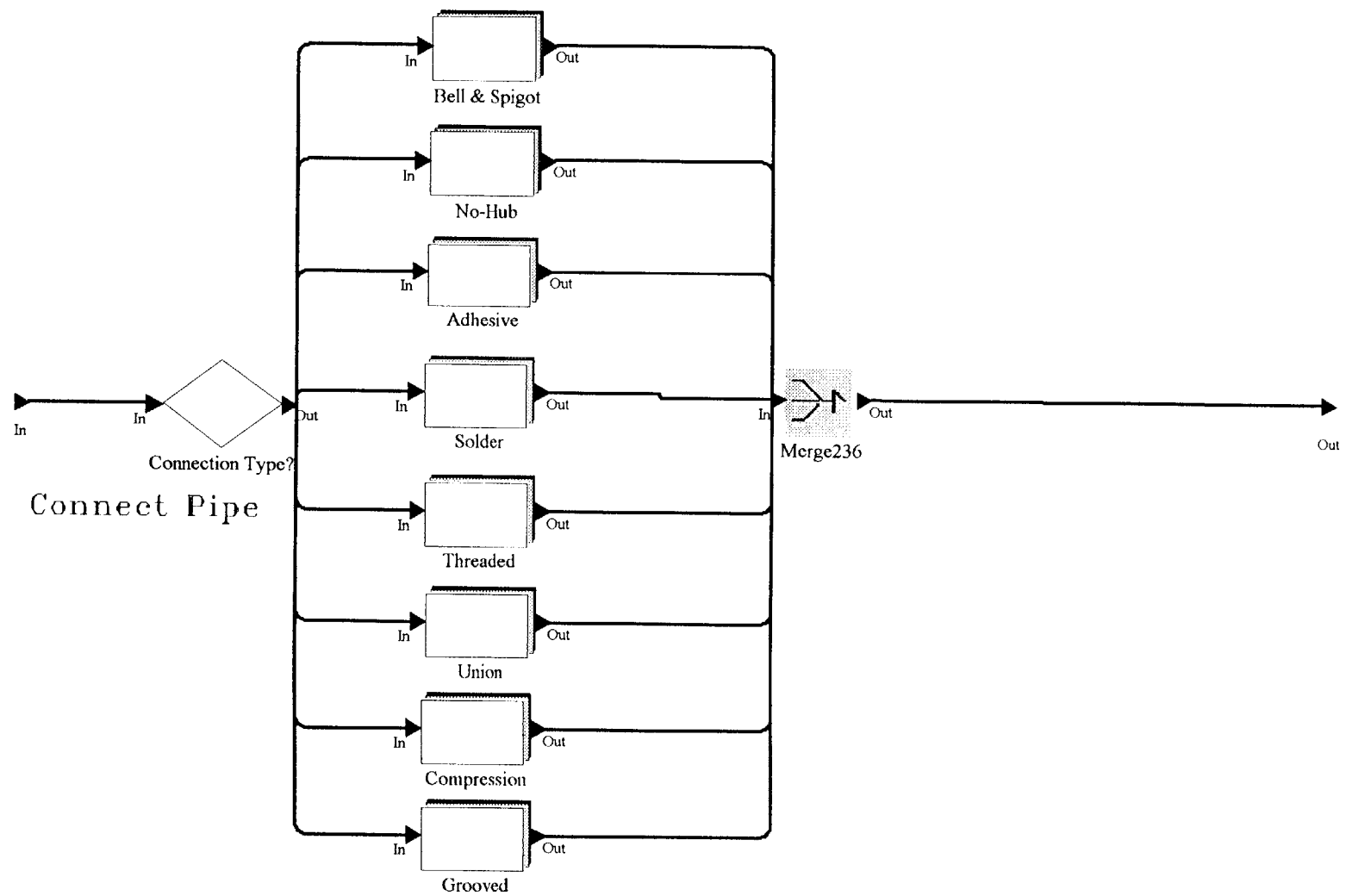
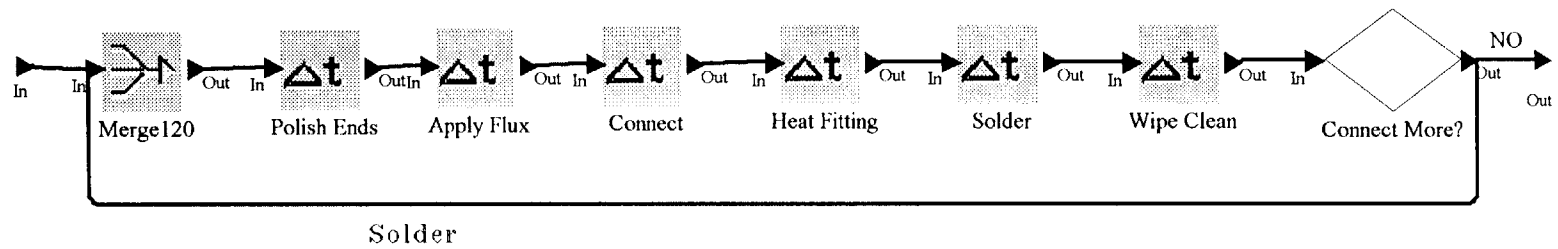


Figure C.8: Place Pipe in Trench



**Figure C.9: Connect Pipe**



**Figure C.10: Connect Pipe (Soldered Connection)**

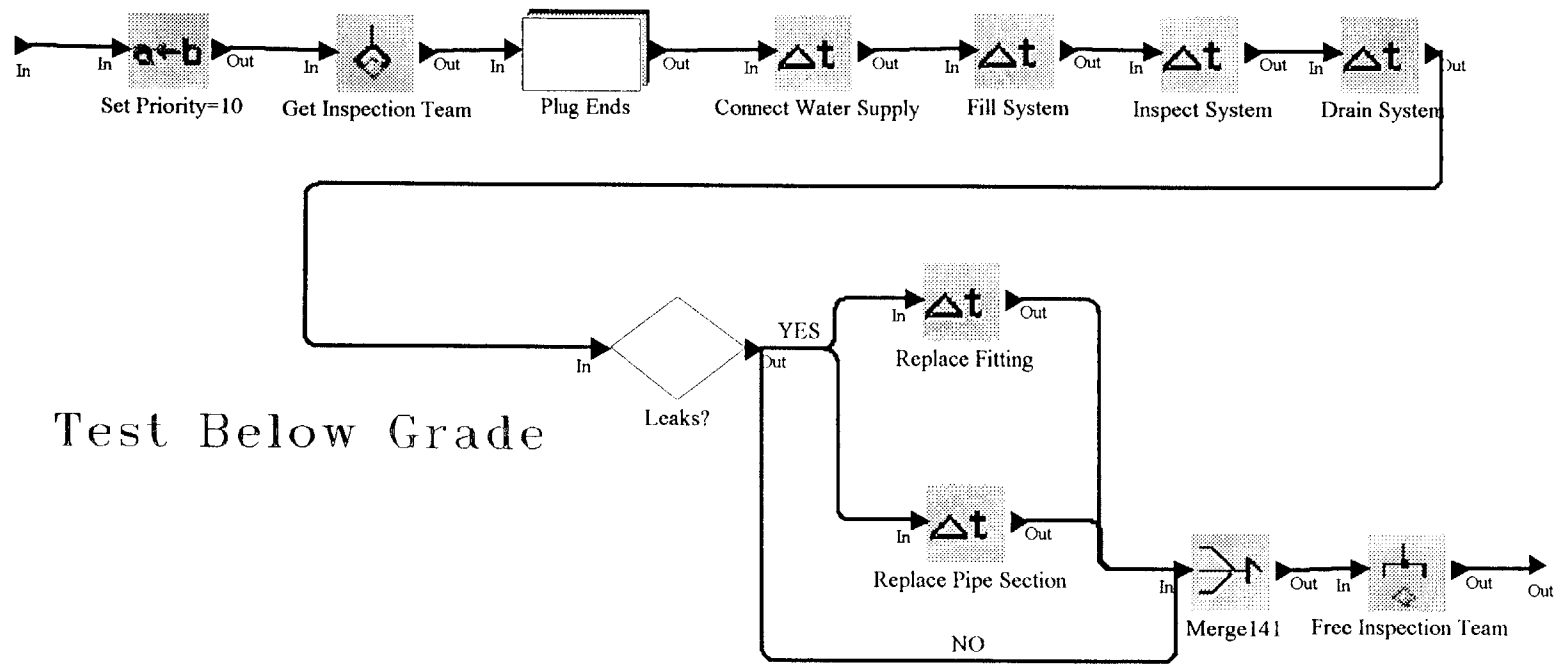
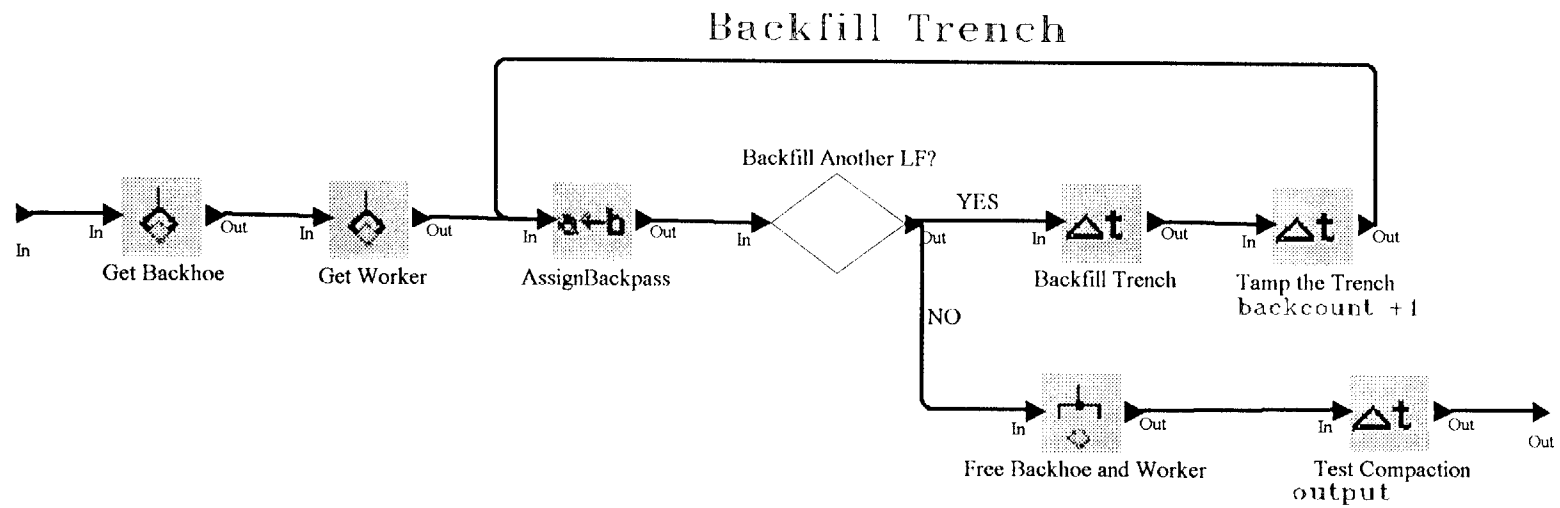


Figure C.11: Test Sub-Grade Piping



**Figure C.12: Backfill Trench**

## Rough-In Horizontal System

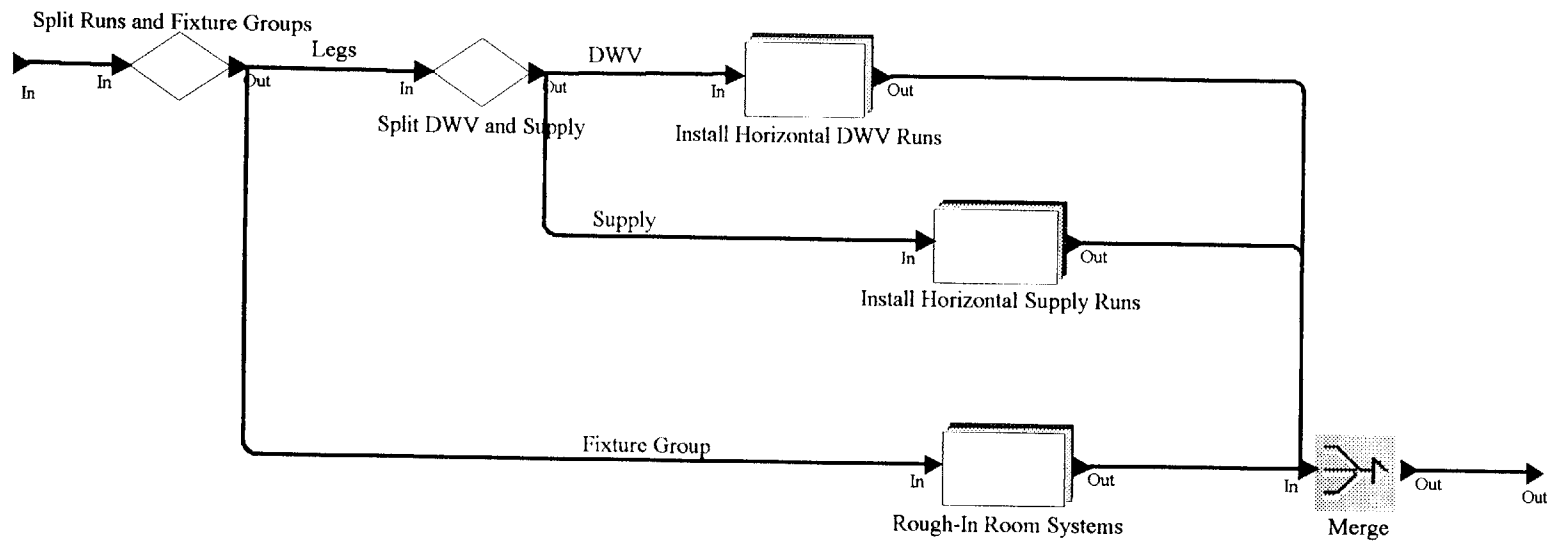


Figure C.13: Rough-In Horizontal System



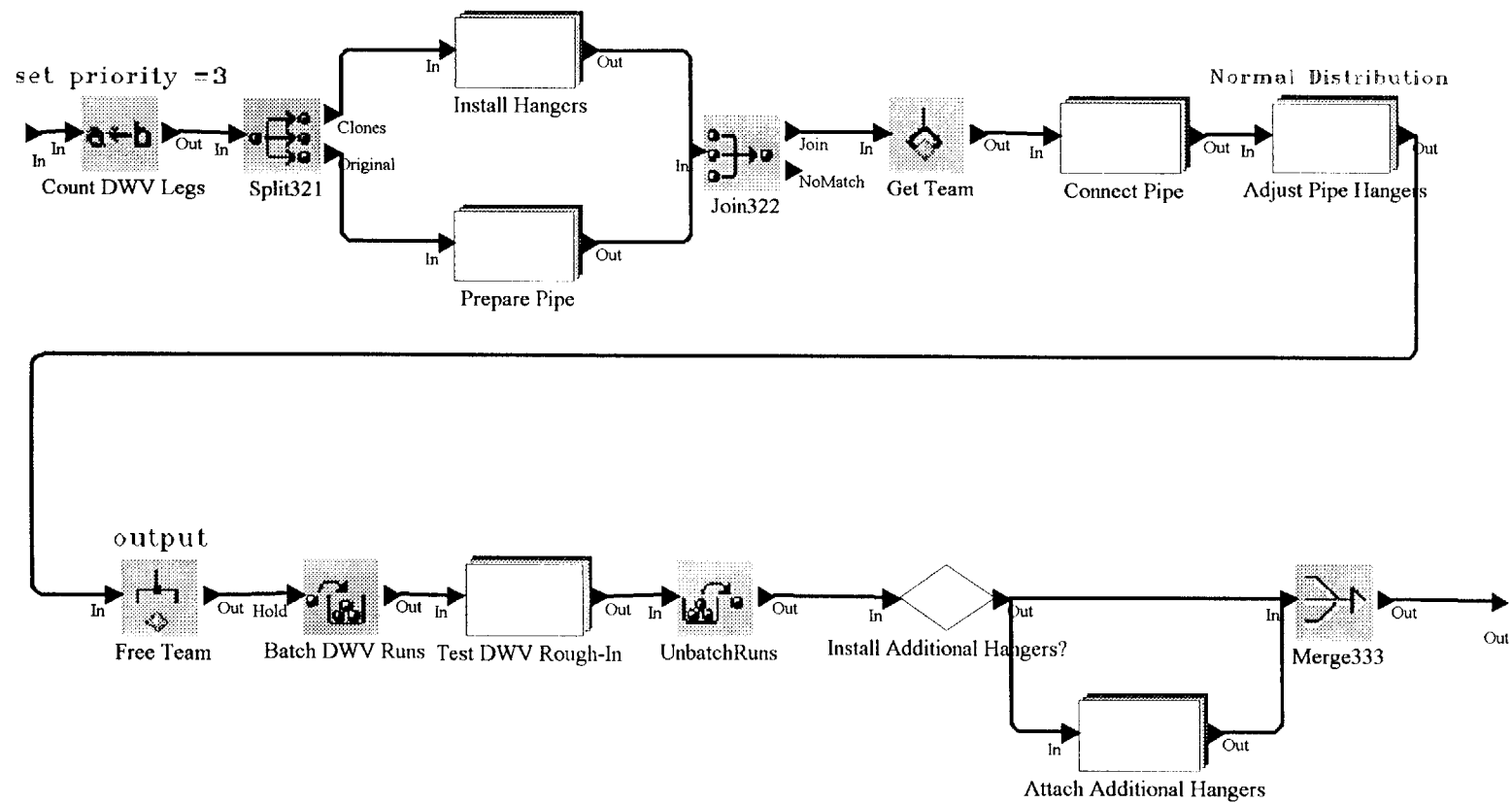


Figure C.14: Install Horizontal DWV Piping

## Support Pipe - Clevis Hanger

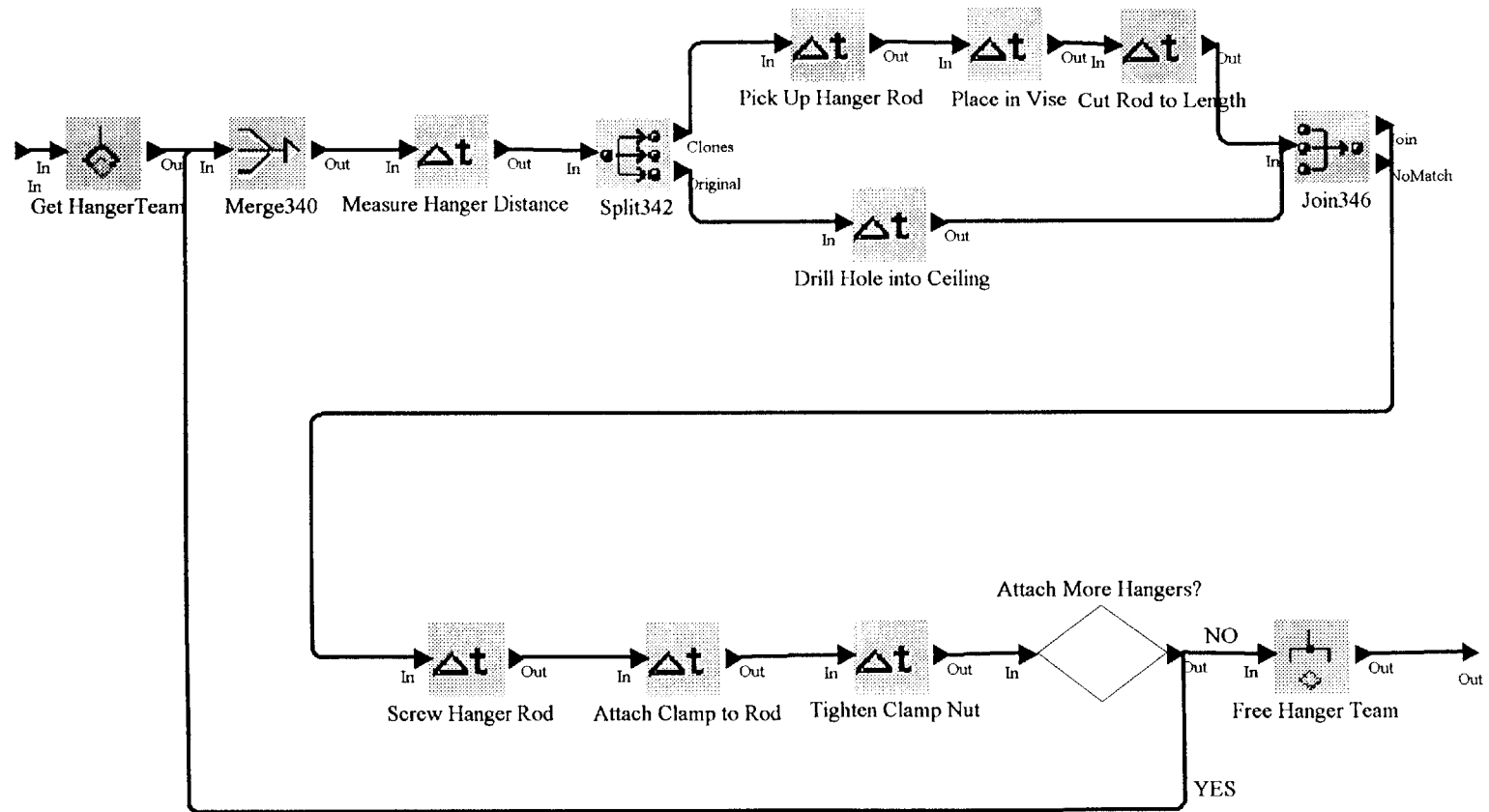
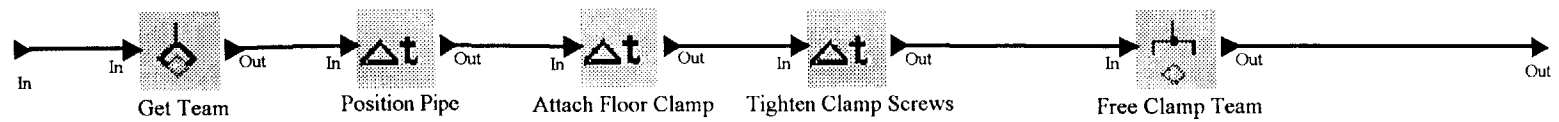


Figure C.15: Support Pipe – Clevis Hanger



## Support Pipe – Vertical Clamp

**Figure C.16: Support Pipe: Vertical Clamp**

## Test DWV Rough-In

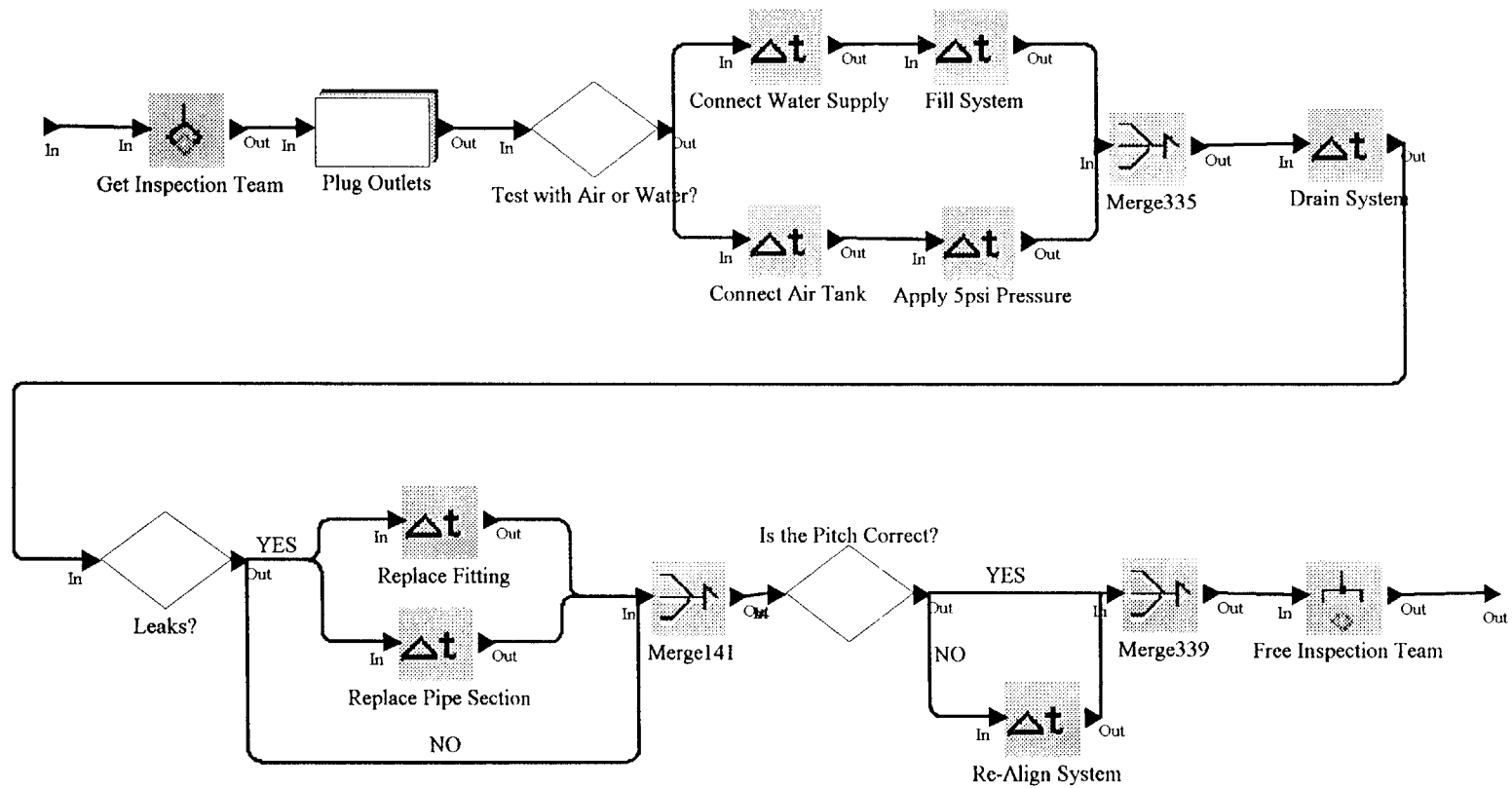


Figure C.17: Test DWV Rough-In

## Install Horizontal Supply Runs

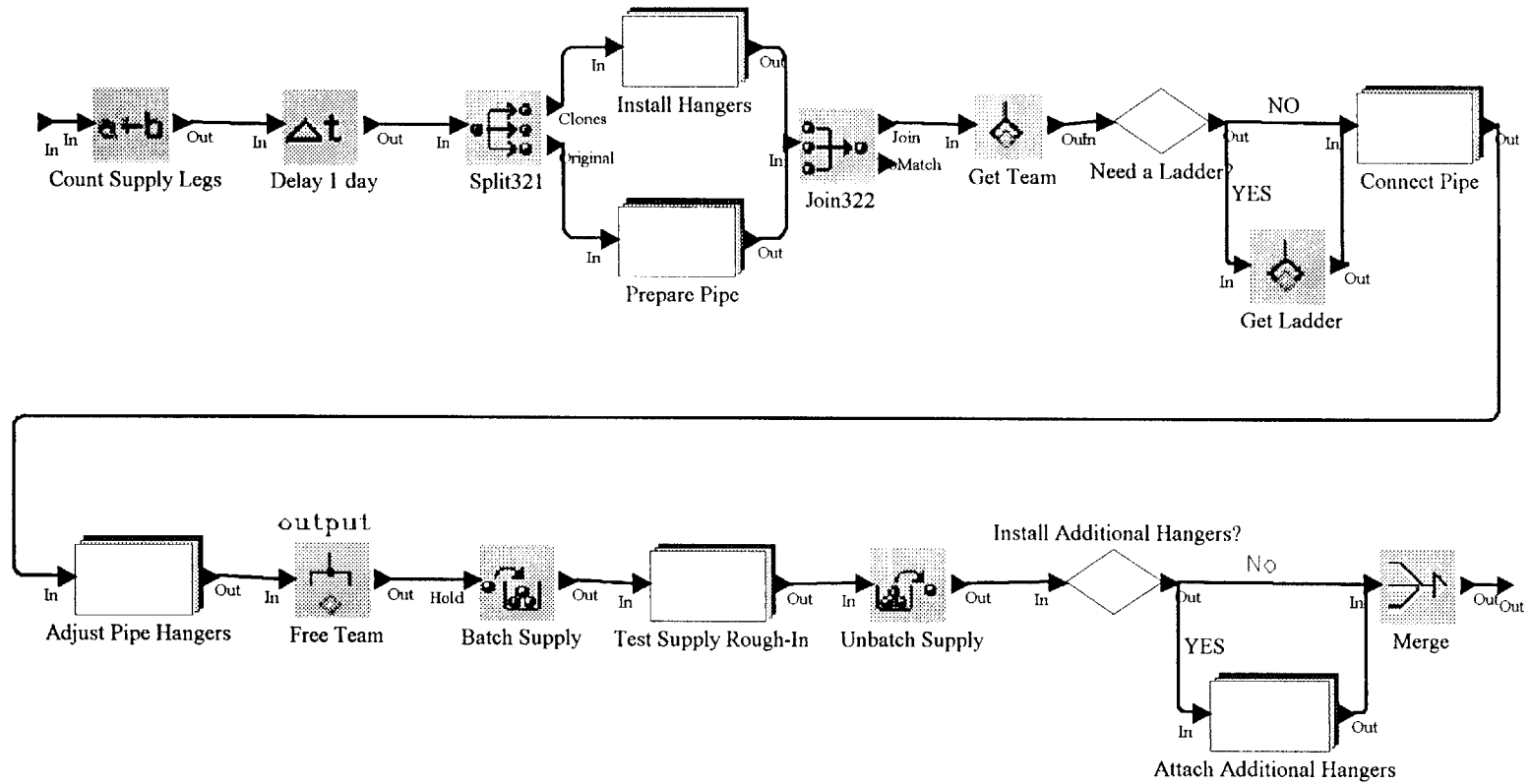


Figure C.18: Install Horizontal Supply Runs

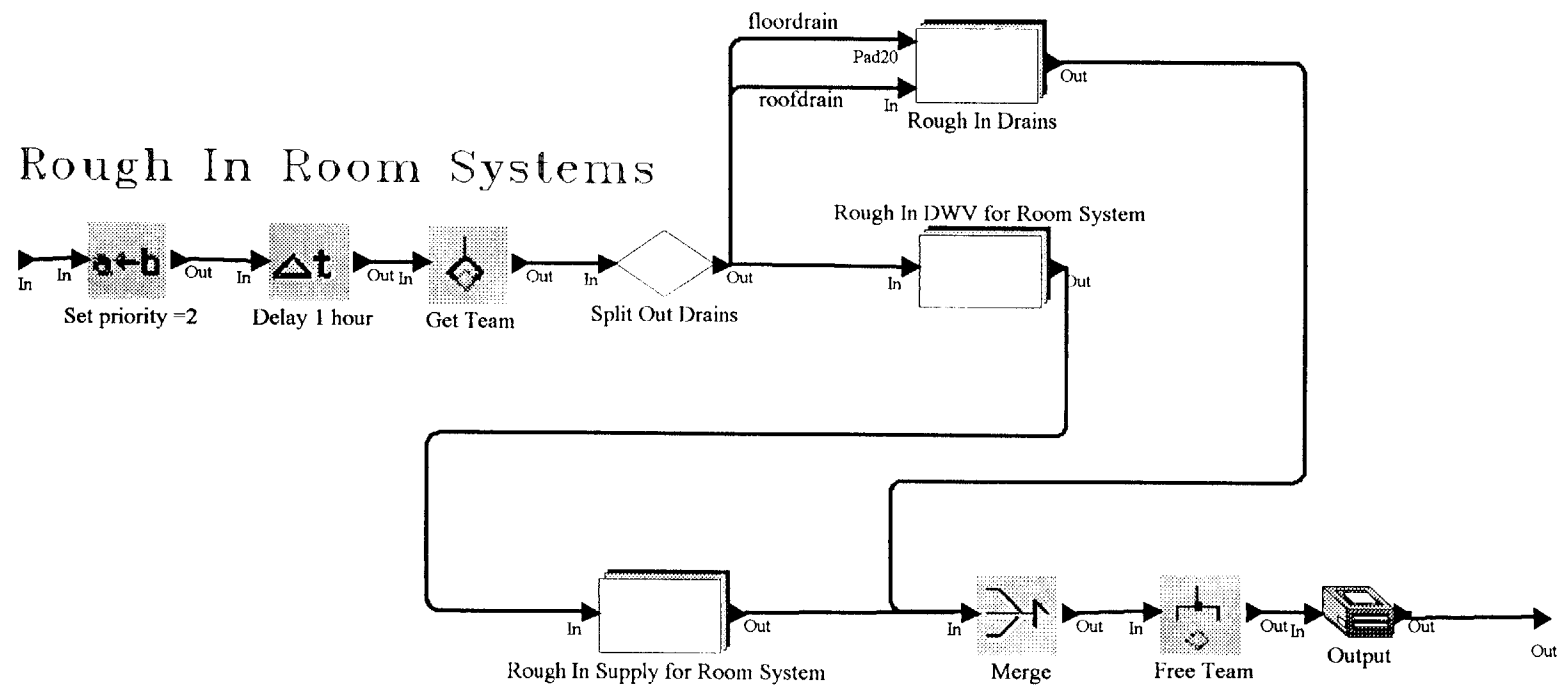
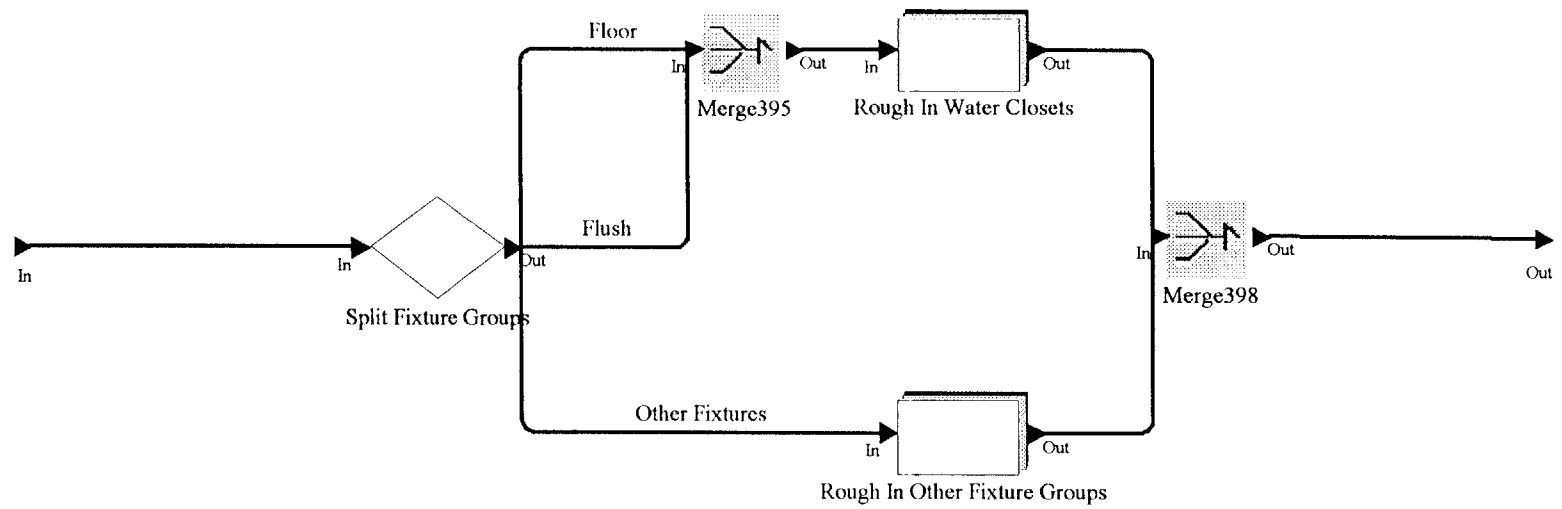
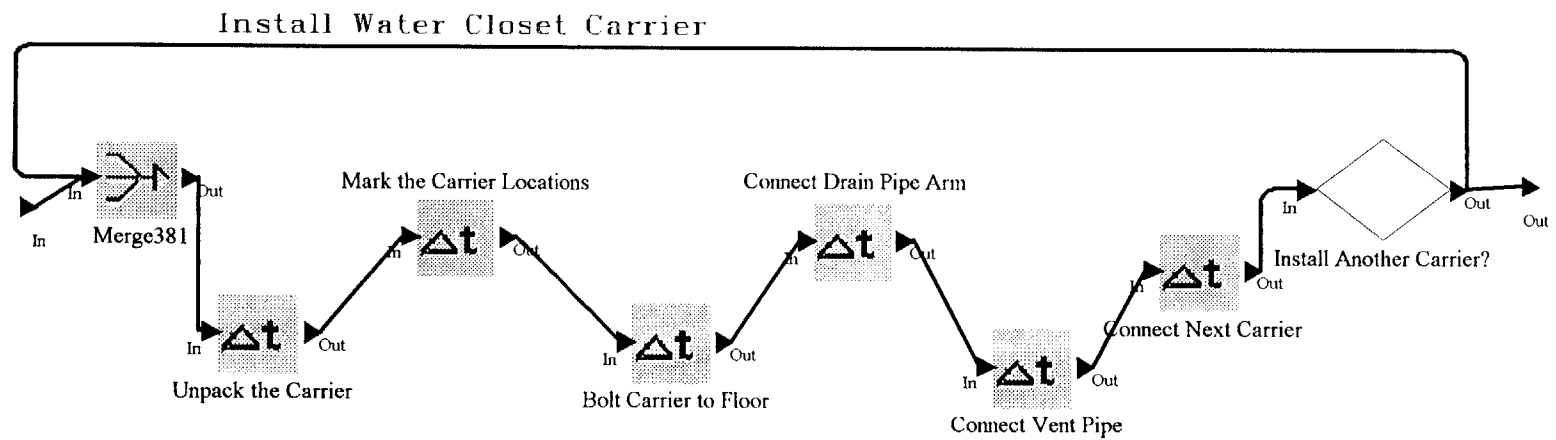


Figure C.19: Rough-In Room Systems

## Rough In DWV for Room System

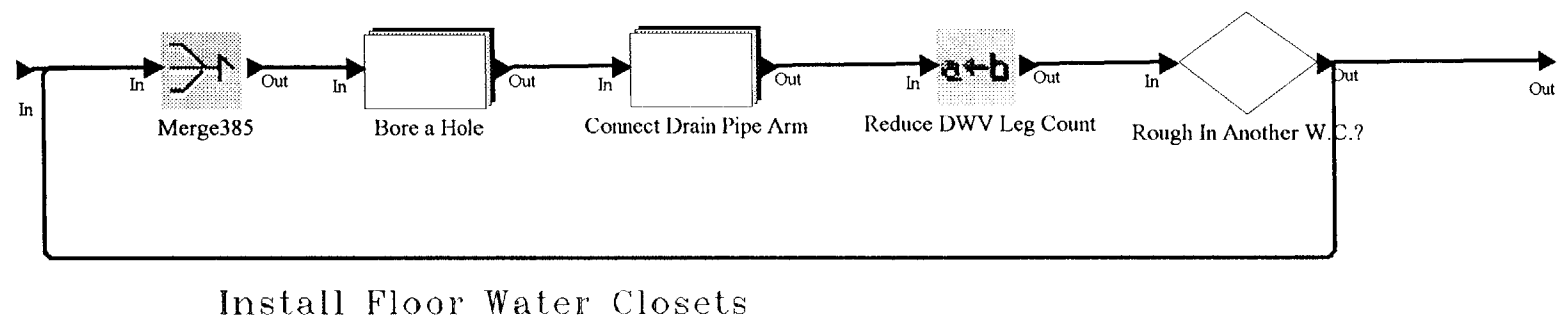


**Figure C.20: Rough-In DWV for a Room System**

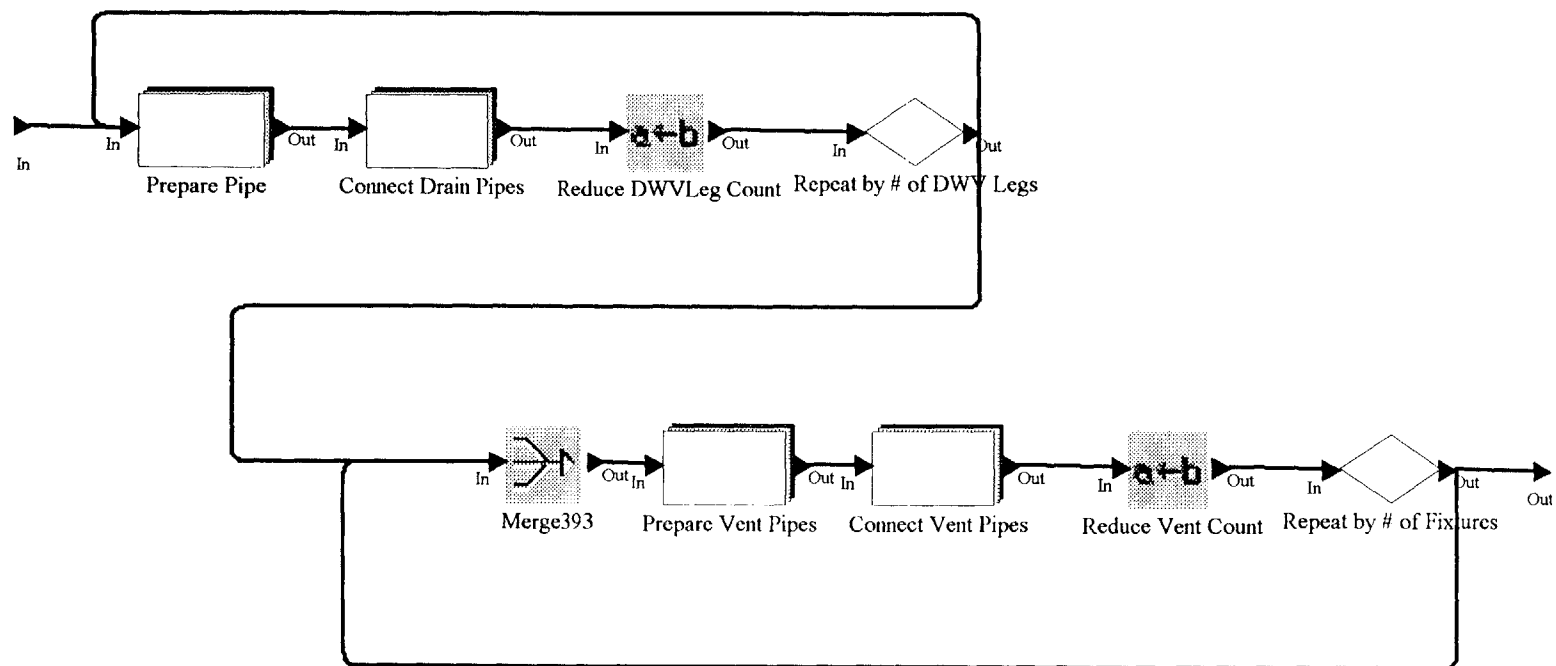


**Figure C.21: Install a Water Closet Carrier**



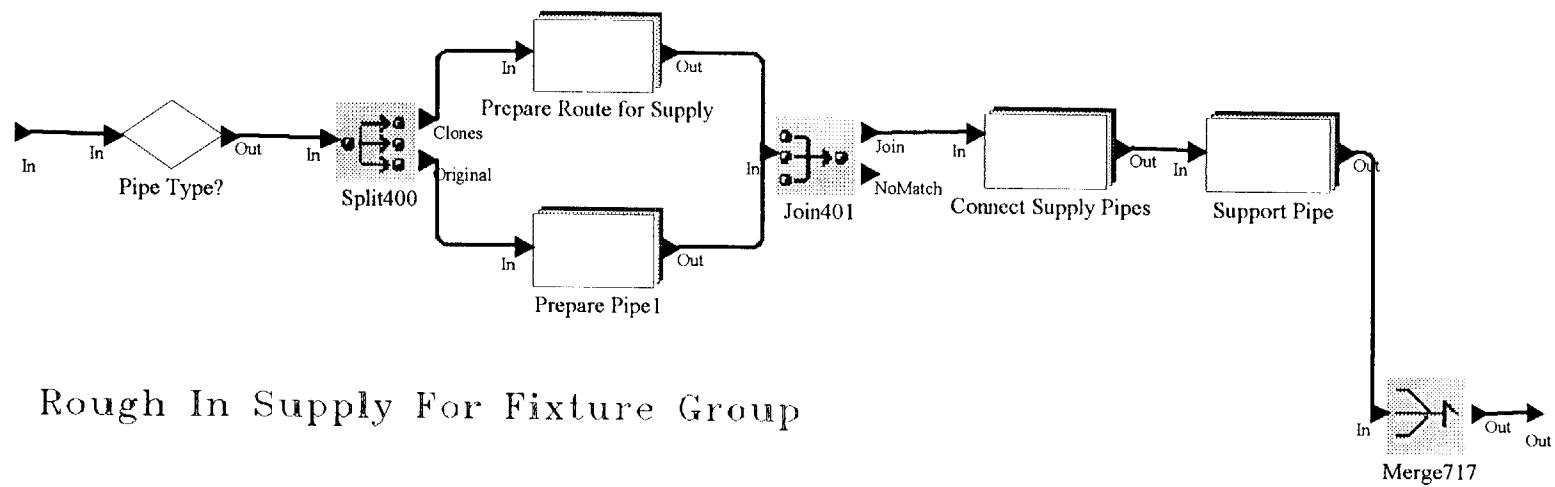


**Figure C.22: Install a Floor Water Closet**



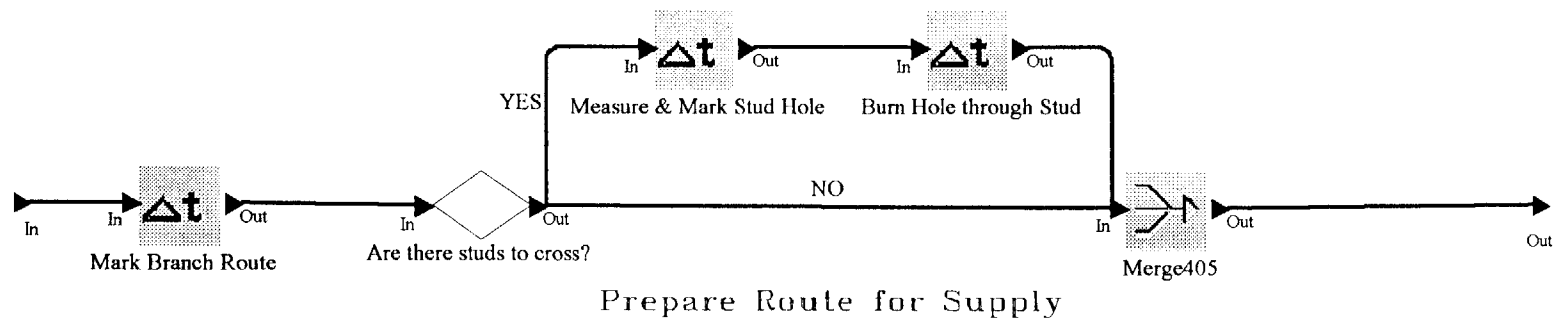
Rough In Other Fixture Groups for DWV

Figure C.23: Rough-In Fixture Groups for DWV

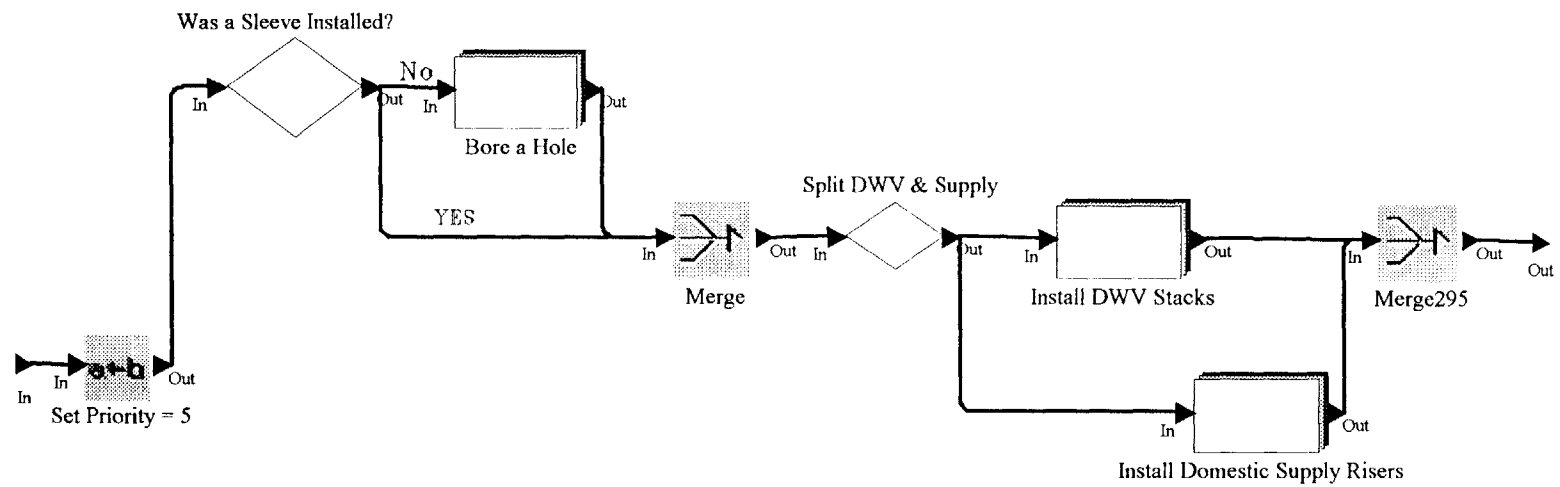


Rough In Supply For Fixture Group

Figure C.24: Rough-In Supply for a Fixture Group

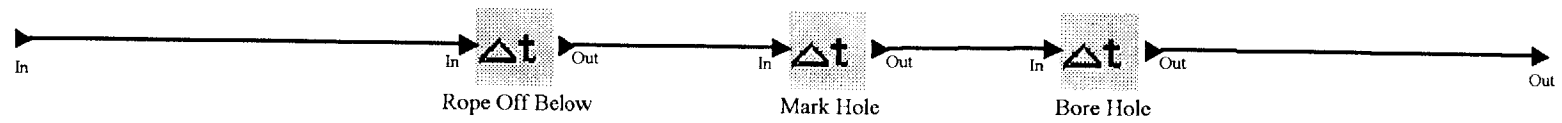


**Figure C.25: Prepare Route for Supply Branches**



## Install Stacks and Risers

Figure C.26: Install Stacks and Risers



Bore A Hole

**Figure C.27: Bore a Hole**

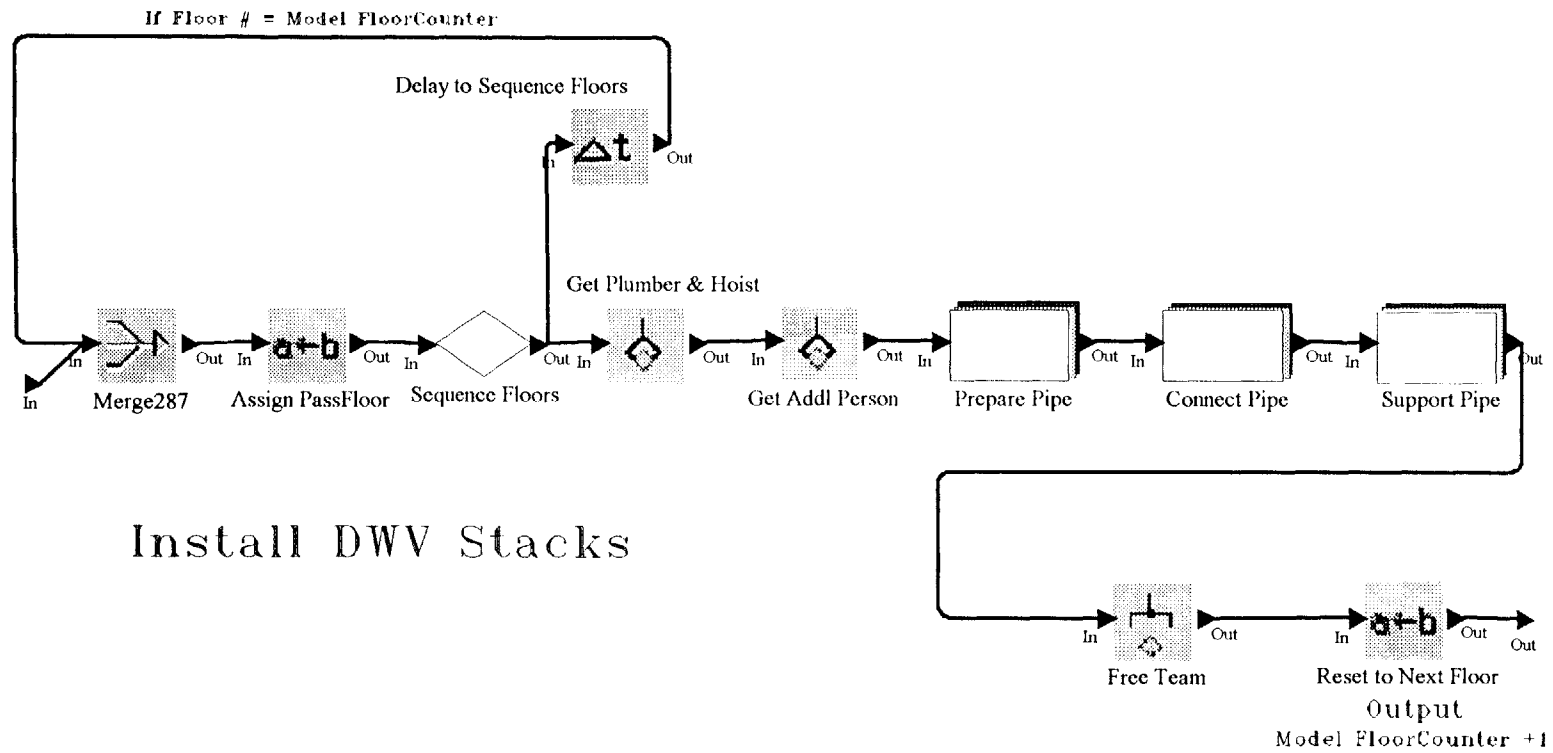


Figure C.28: Install DWV Stacks

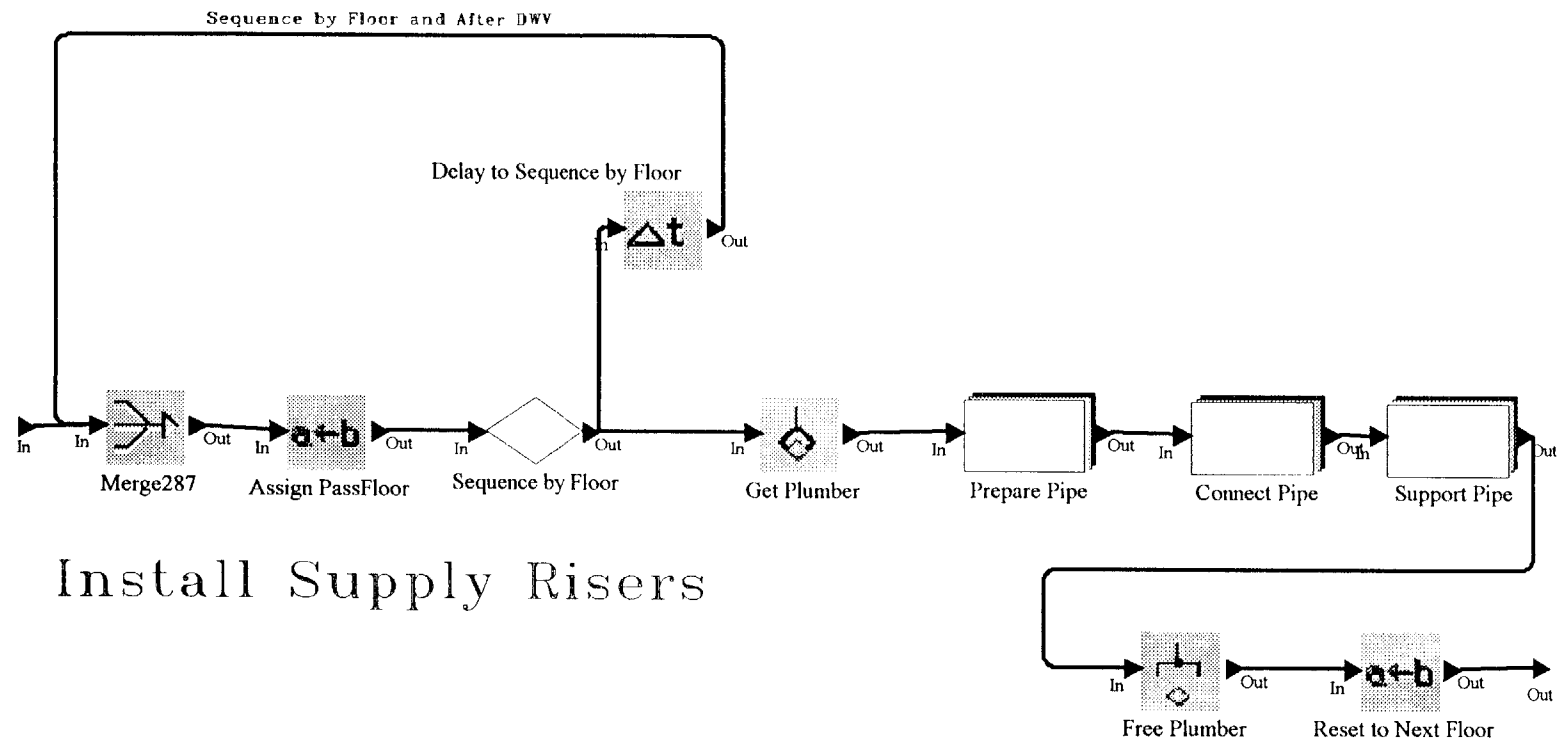
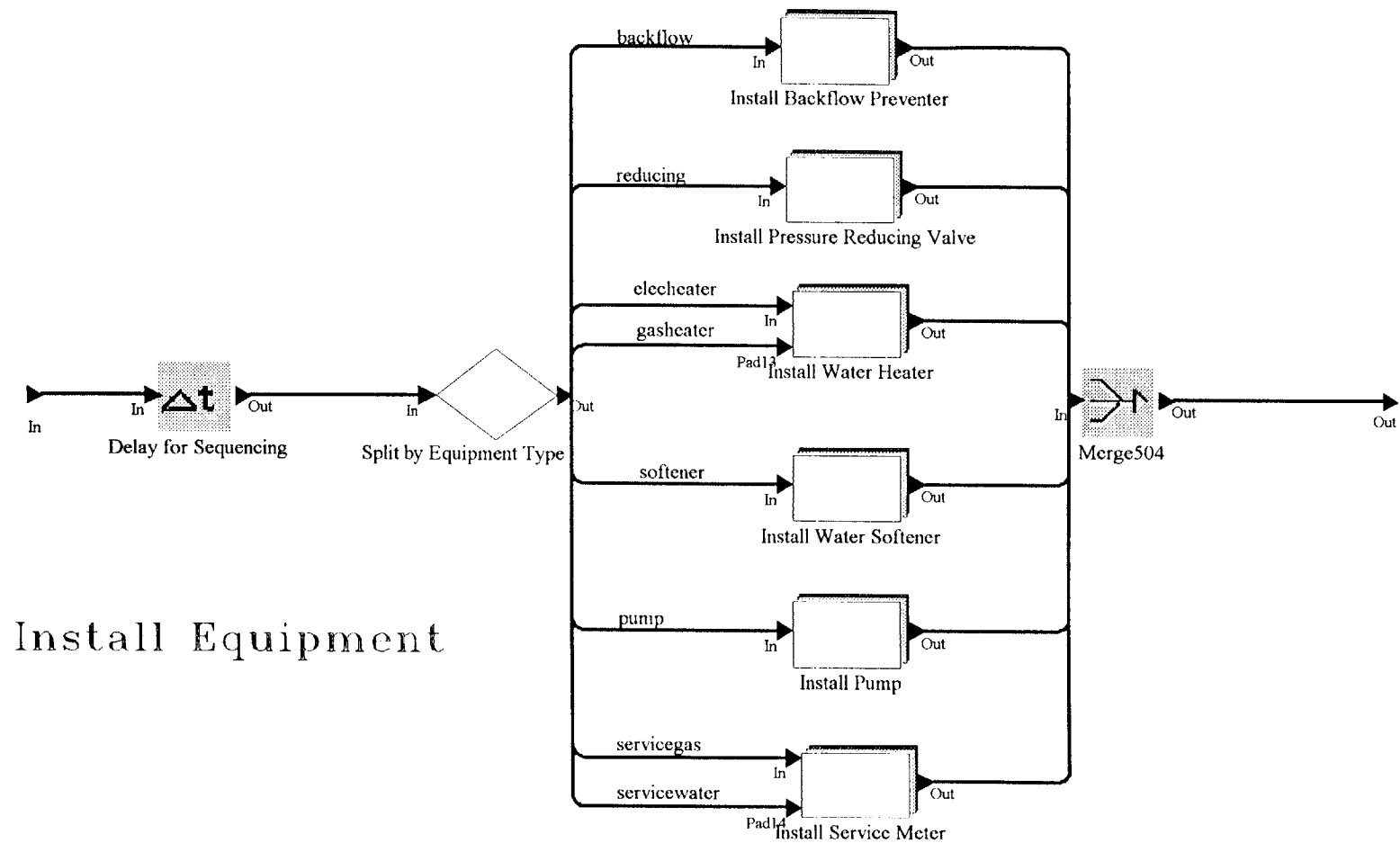


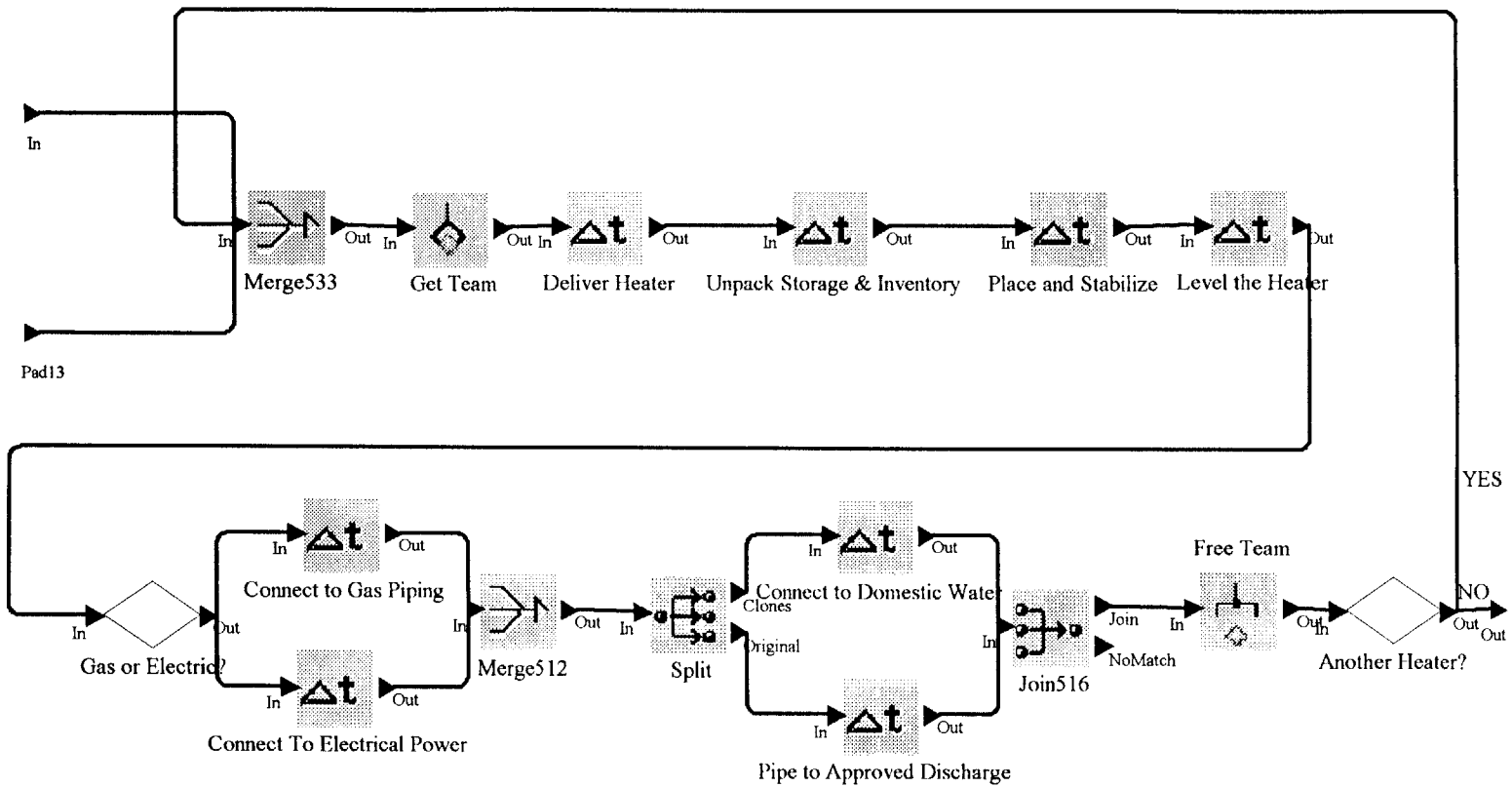
Figure C.29: Install Supply Risers





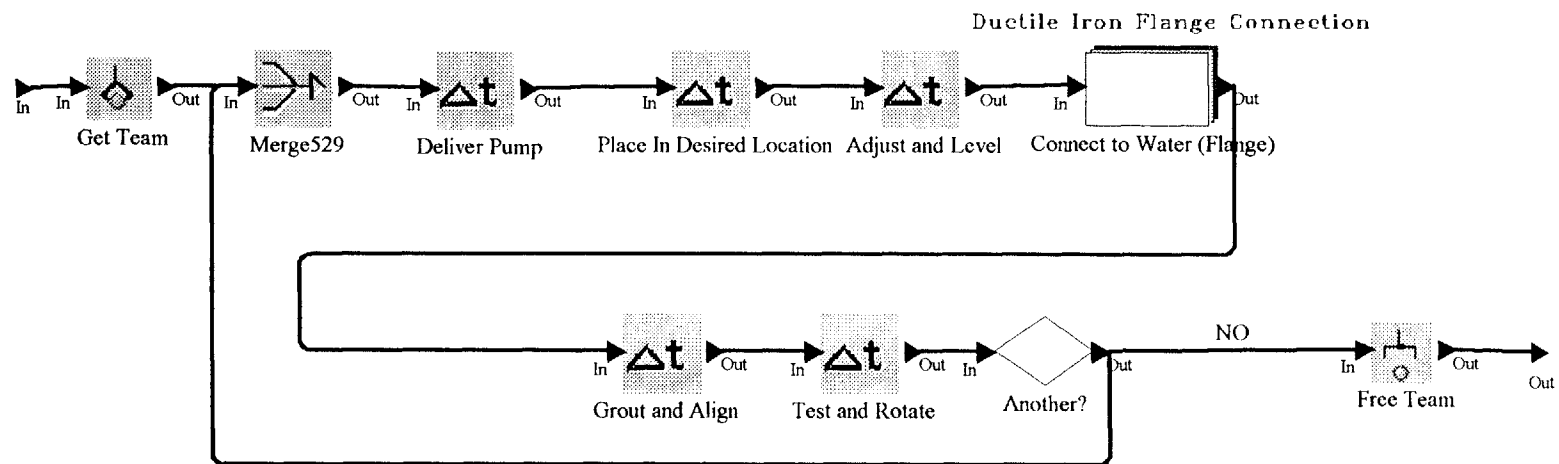
## Install Equipment

Figure C.30: Install Equipment



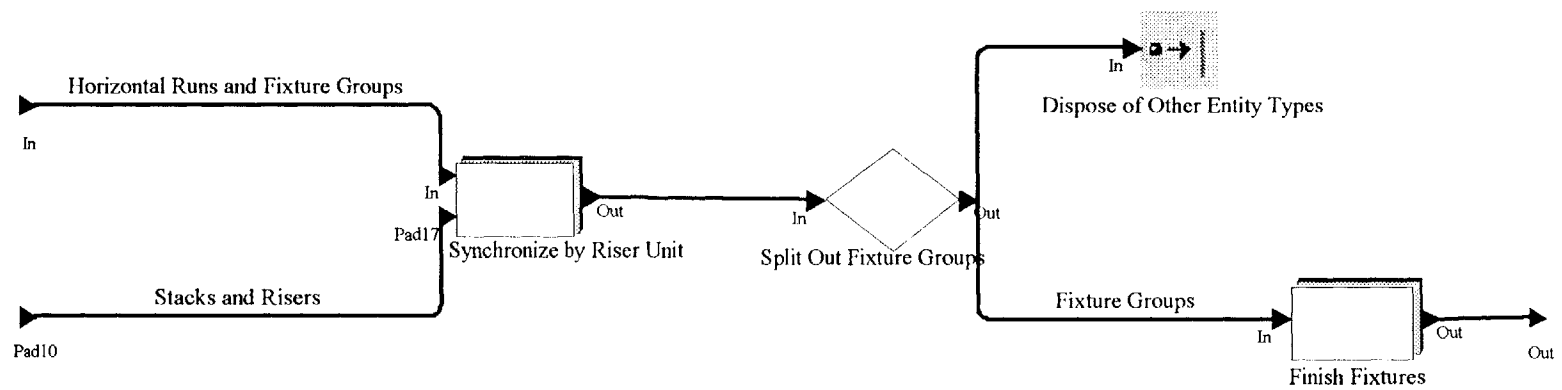
## Install A Water Heater

Figure C.31: Install a Water Heater



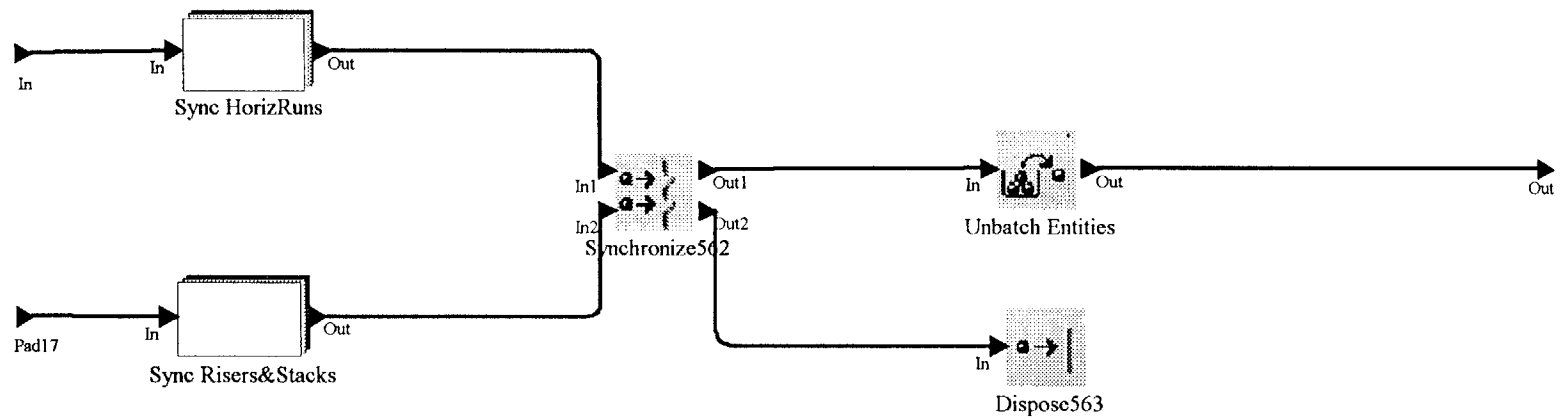
## Install A Water Booster Pump

Figure C.32: Install a Water Booster Pump



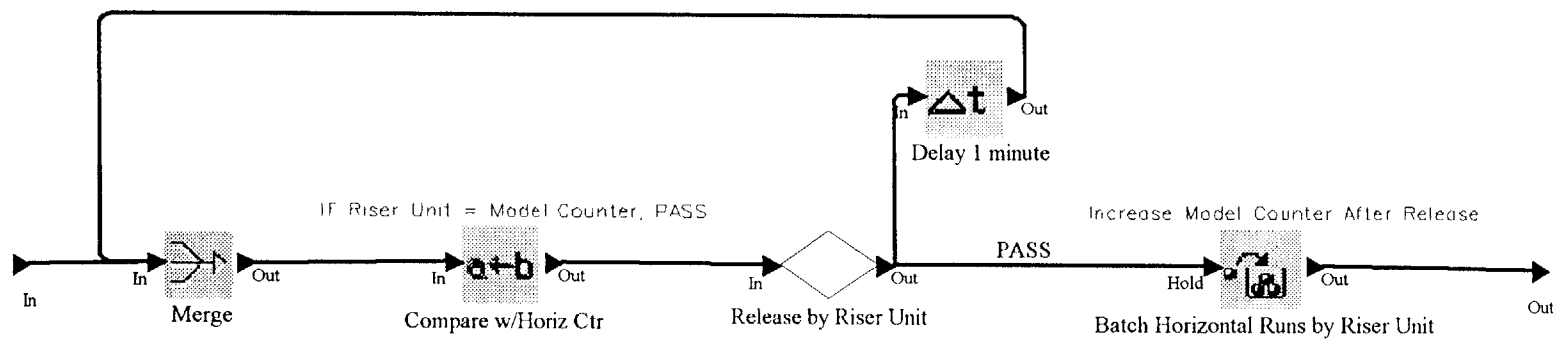
Finish Rooms

Figure C.33: Finish Rooms



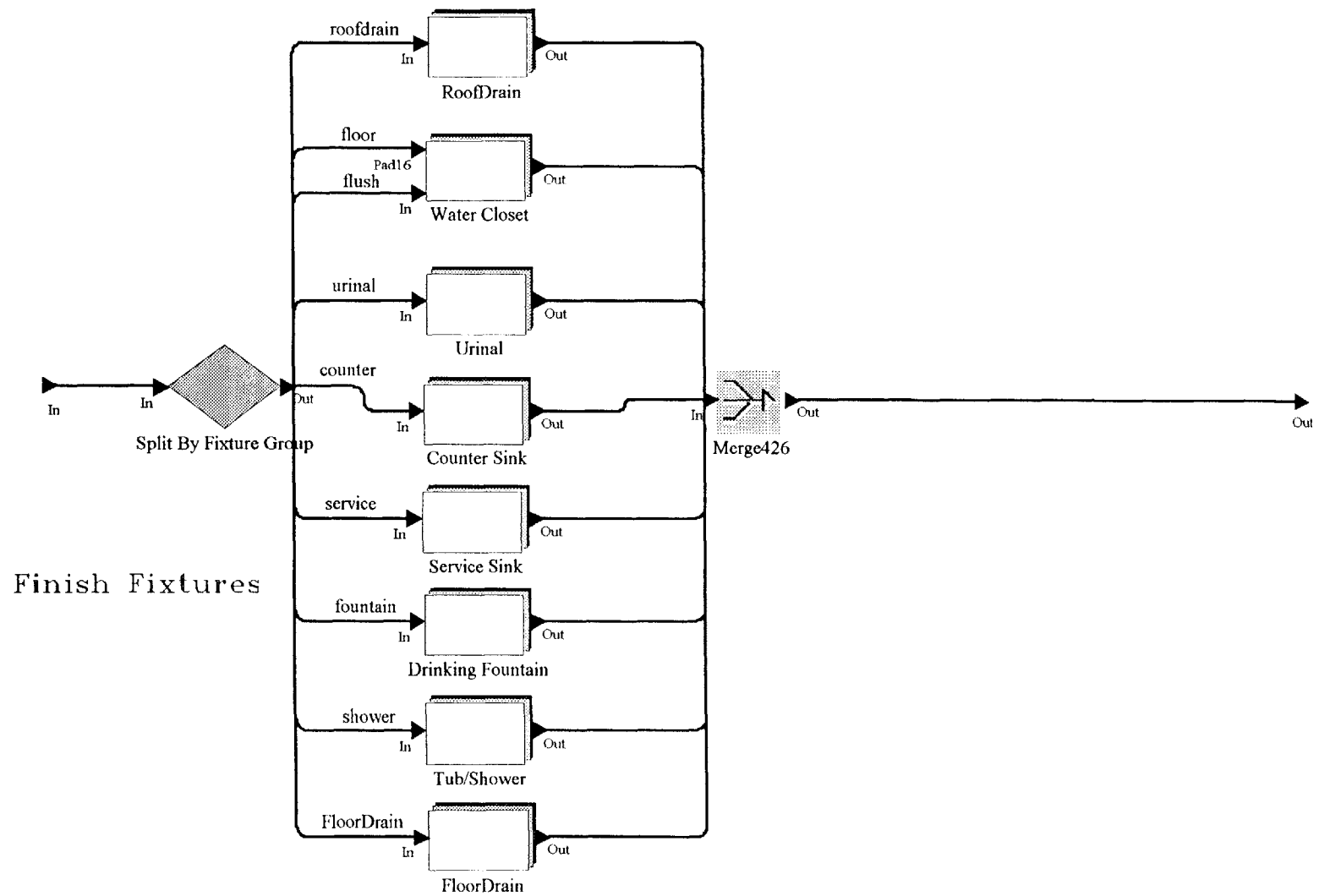
## SYNCHRONIZE BY RISER UNIT

Figure C.34: Synchronize Entities by Riser Unit



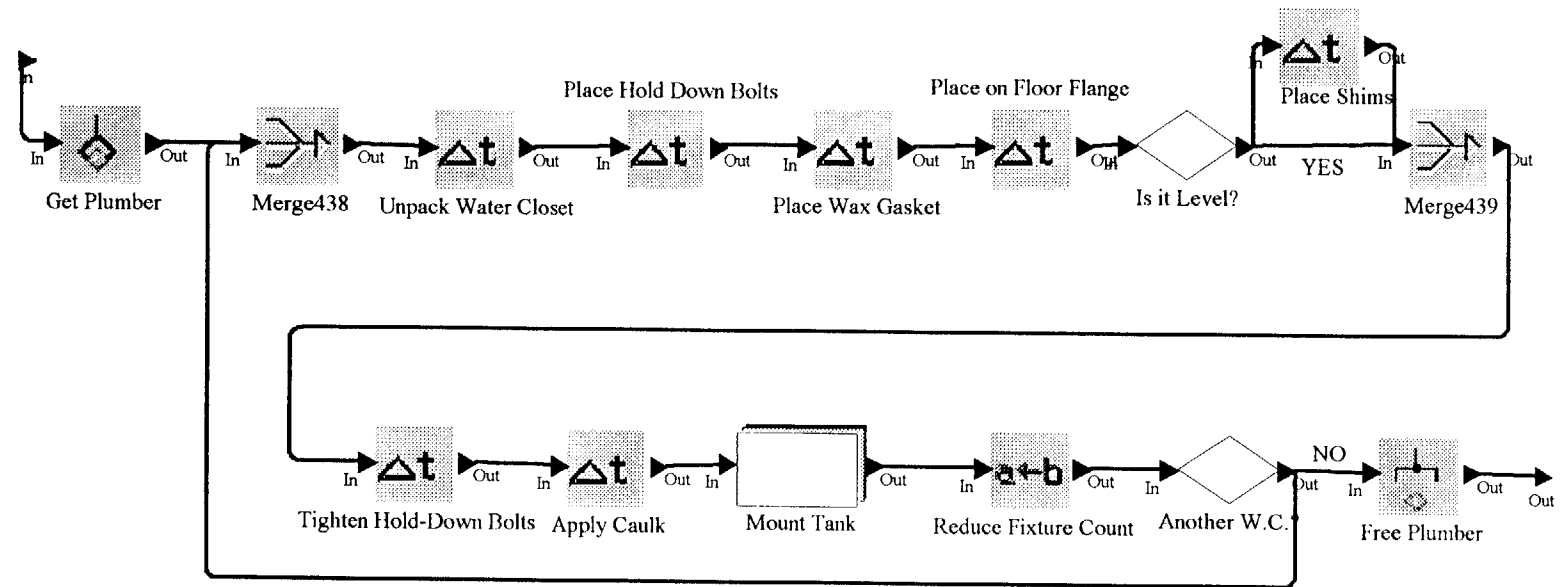
## Synchronize Horizontal Runs

Figure C.35: Synchronize Horizontal Runs



Finish Fixtures

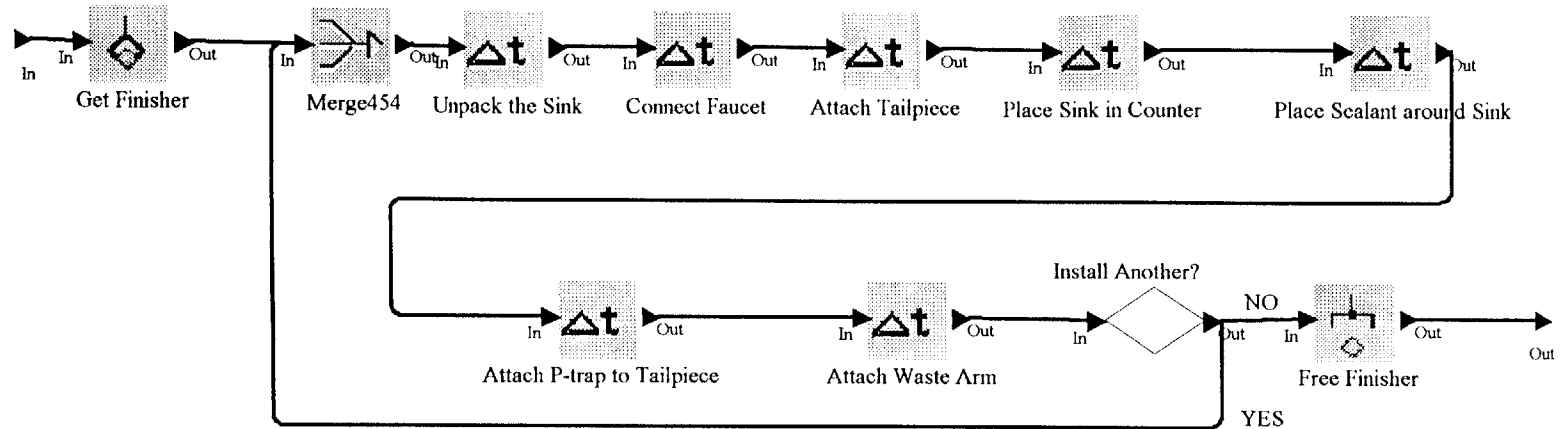
Figure C.36: Finish Fixtures



Install A Floor Mounted Water Closet

Figure C.37: Install a Floor Mounted Water Closet



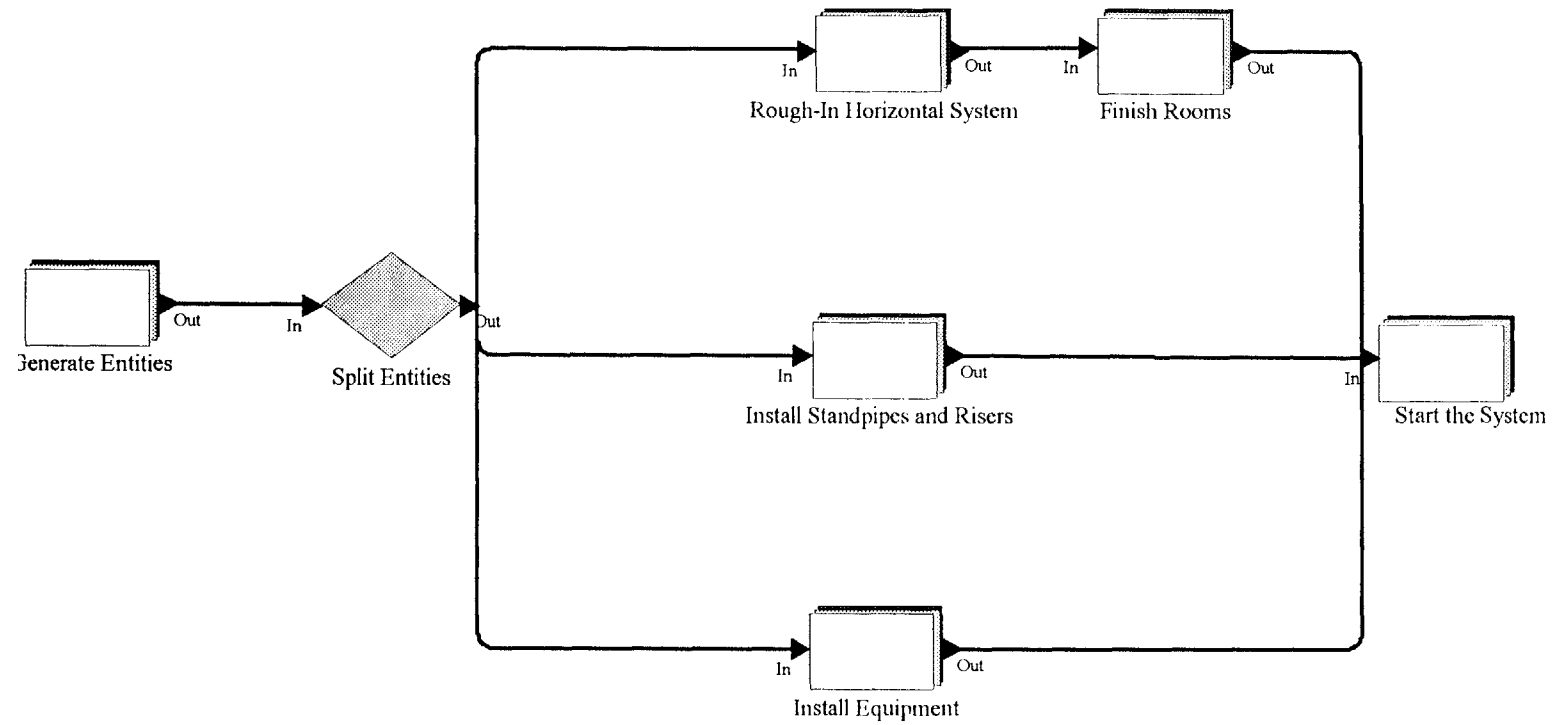


## Install Counter Sink

Figure C.38: Install a Counter-Top Sink



## **Appendix D: Computer-Based Model Layout for Fire Protection Installation**



**Figure D.1: Overall Process for Fire Protection Installation**

## Process Entities & Assign Attributes

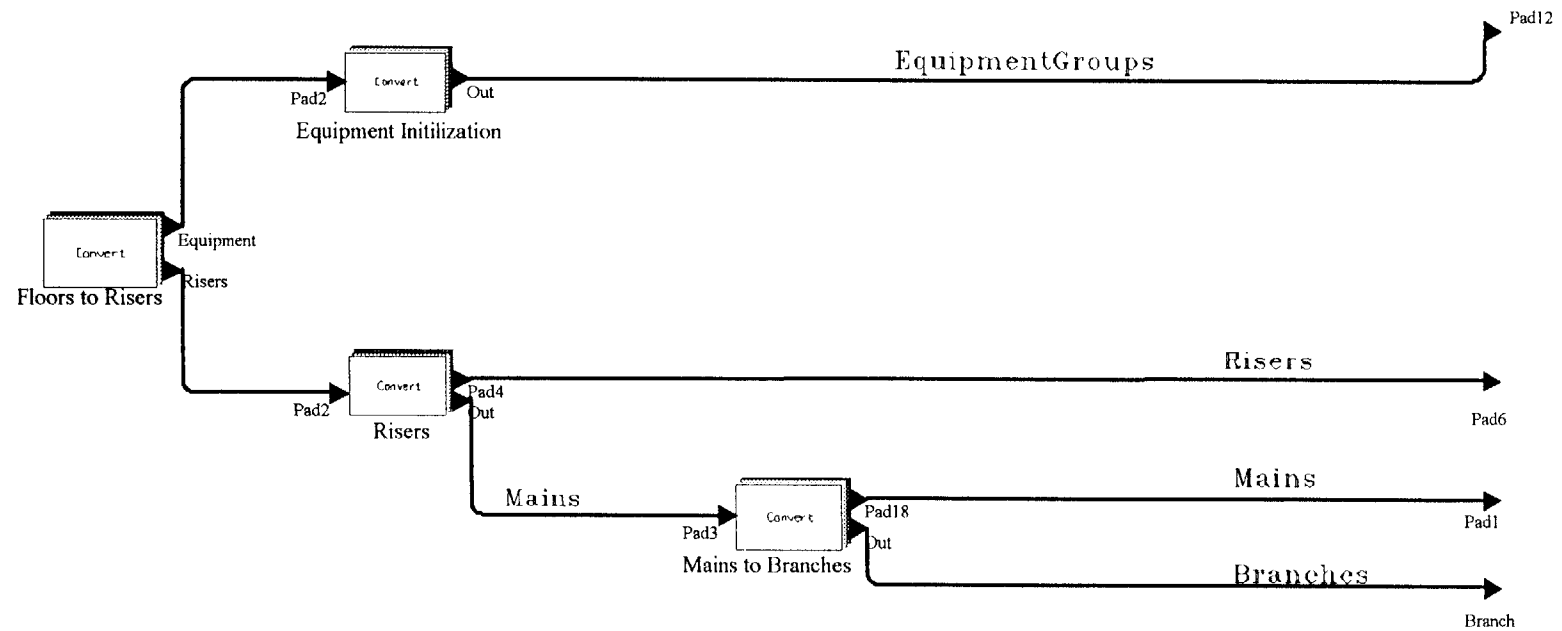


Figure D.2: Process Entities and Assign Attributes

## Rough-In Horizontal Systems

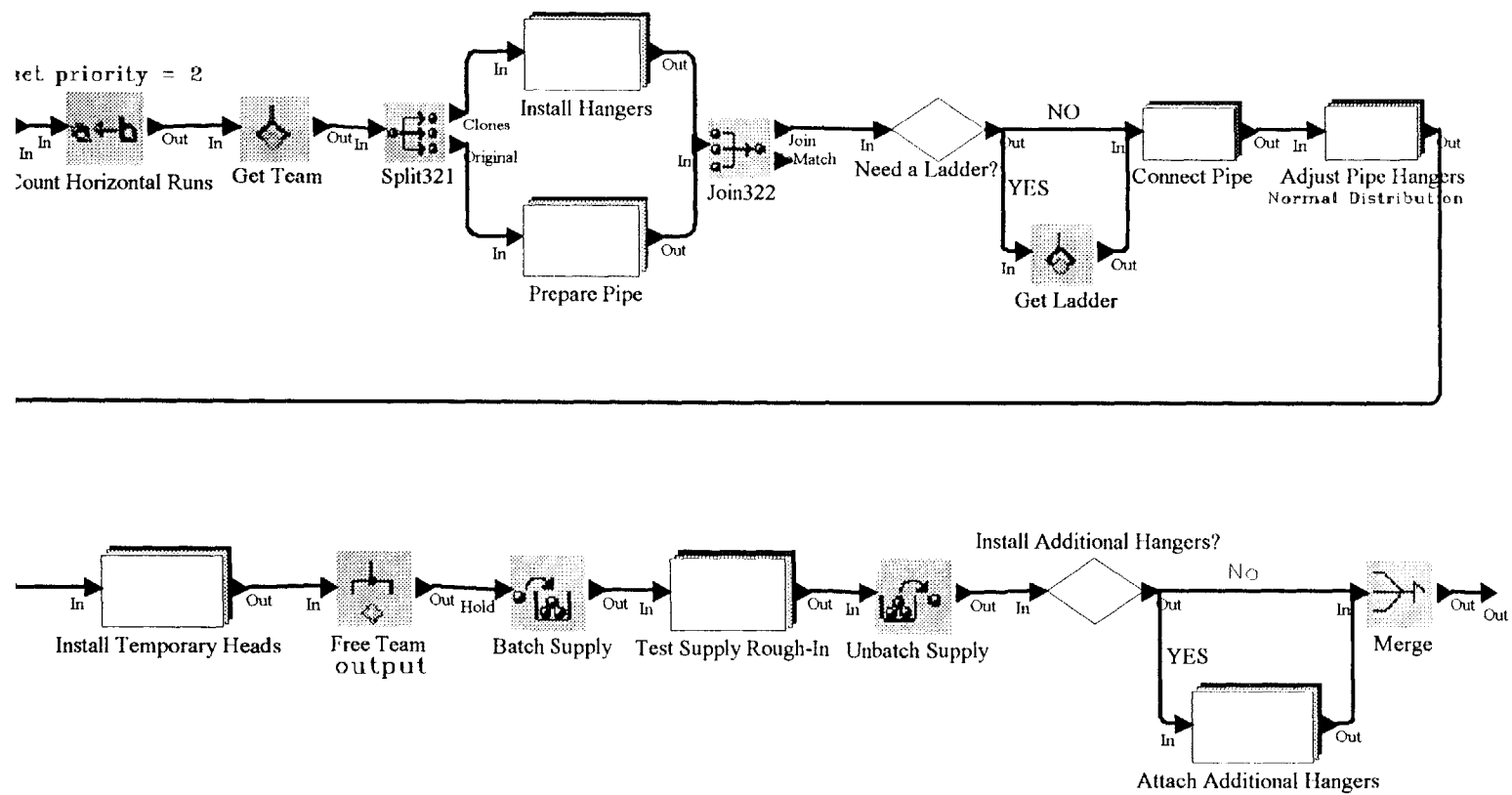
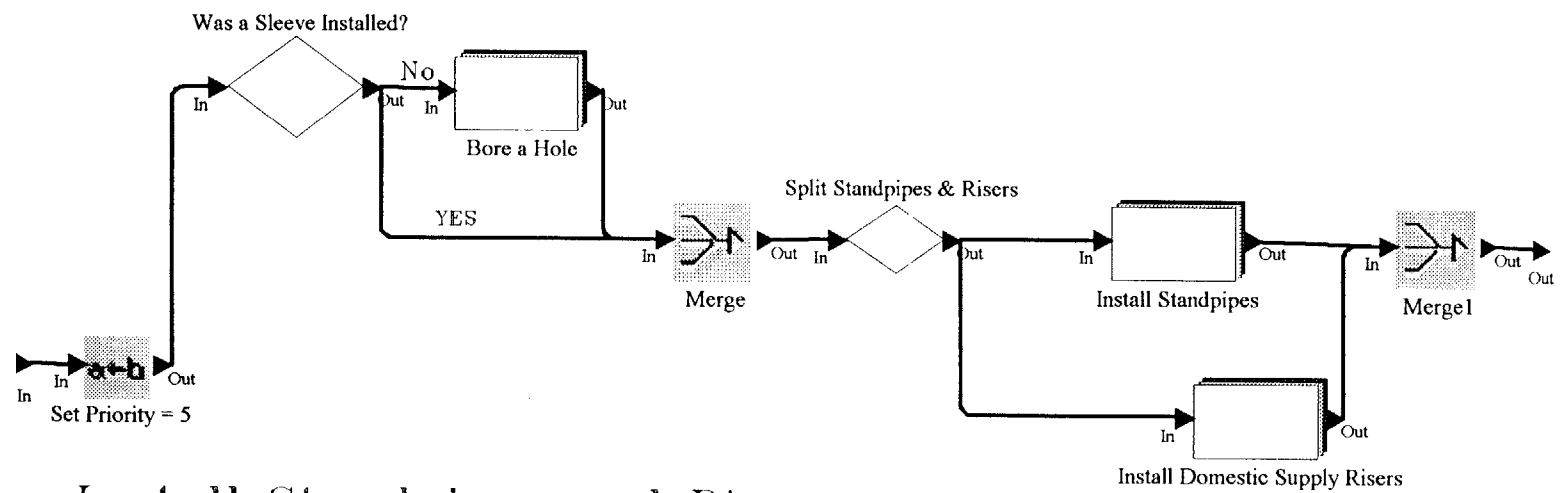
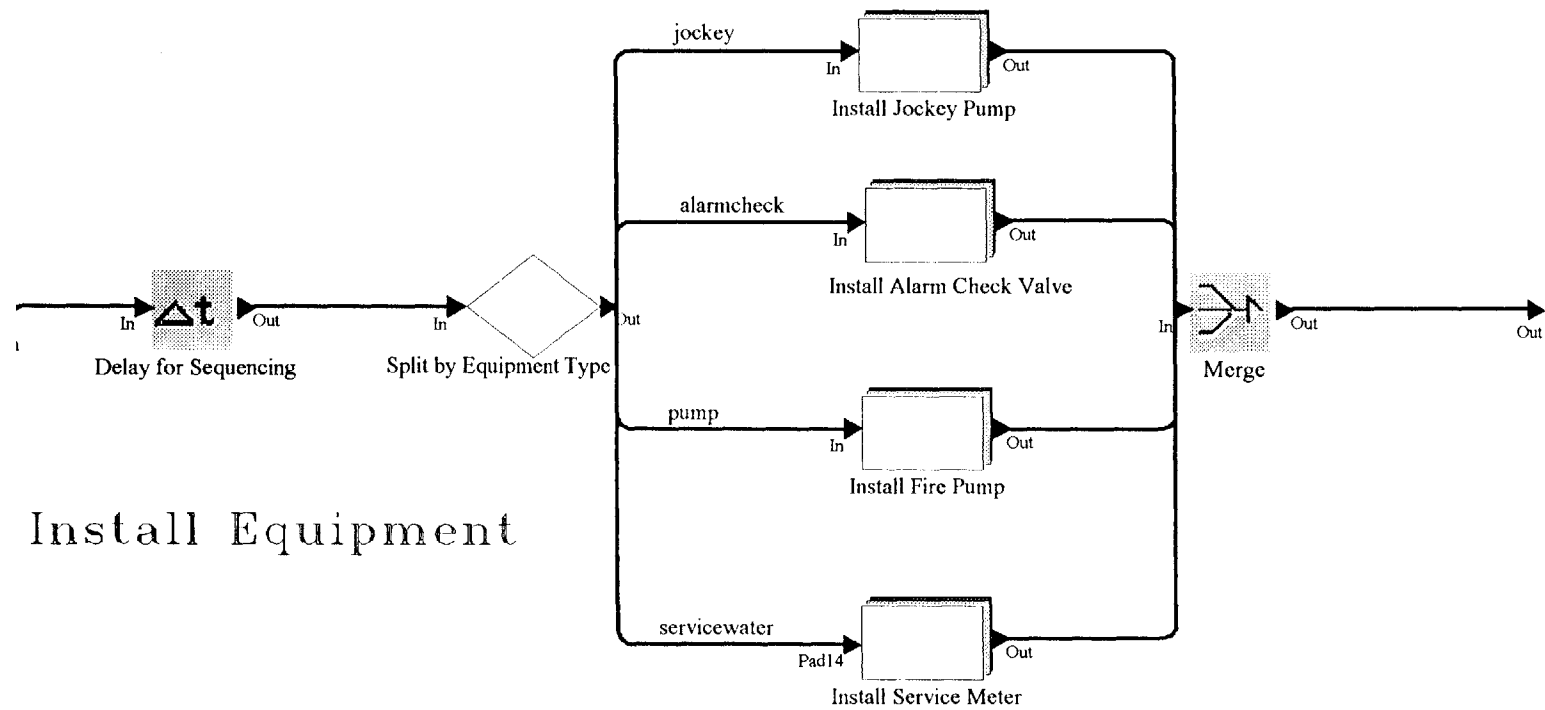


Figure D.3: Rough-In Horizontal Systems



## Install Standpipes and Risers

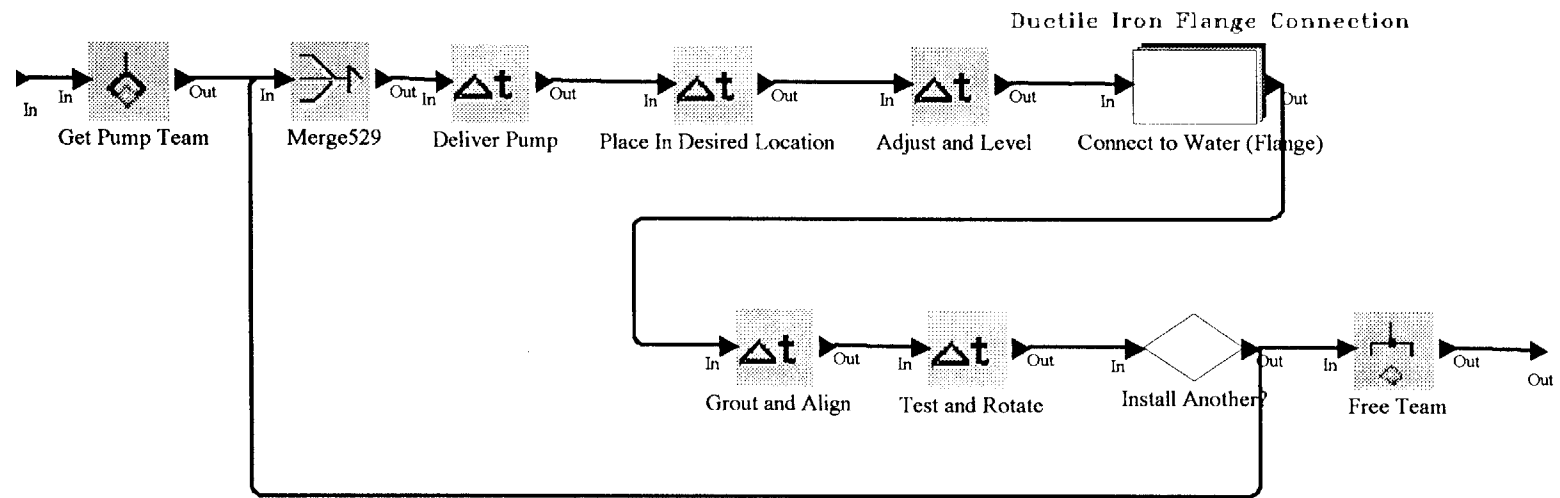
Figure D.4: Install Standpipes and Risers



## Install Equipment

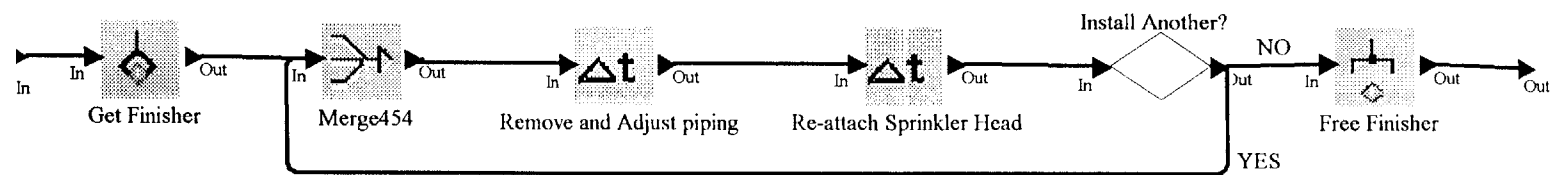
Figure D.5: Install Equipment





Install Fire Pump

Figure D.6: Install Fire Pump



## Install Sprinkler Heads

Figure D.7: Install Sprinkler Heads

## **Appendix E: Cost Calculations for Innovations**

### Cost Summary for Plumbing with Flexible Piping

	Direct Labor (inc. Union Dues)	Workmen's Comp. etc. (26%)	O&P (29%) (inc. Tax, Insurance)	Cost per Hour	Total # of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	224	\$ 13,593
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	896	\$ 51,969
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	224	\$ 11,787
Backhoe	\$ 33.11	\$ 8.61	\$ 9.60	\$ 51.32	60	\$ 3,079
Operator	\$ 33.83	\$ 8.80	\$ 9.81	\$ 52.44	60	\$ 3,146
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 83,575</b>

### Cost Summary for Plumbing with Roll Grooved Fittings

	Direct Labor (inc. Union Dues)	Workmen's Comp. etc. (26%)	O&P (29%) (inc. Tax, Ins.)	Cost per Hour	Total # of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	248	\$ 15,049
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	992	\$ 57,537
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	248	\$ 13,050
Backhoe	\$ 33.11	\$ 8.61	\$ 9.60	\$ 51.32	60	\$ 3,079
Operator	\$ 33.83	\$ 8.80	\$ 9.81	\$ 52.44	60	\$ 3,146
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 91,862</b>

### Cost Summary for Fire Protection Installation(with Roll Grooved Fittings)

	Direct Labor (incl. Union Dues)	Workmen's Comp. etc. (26%)	O & P (29%) (incl. Tax, Insurance)	Cost per Hour	Total Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	424	\$ 25,729
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	1696	\$ 98,370
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	424	\$ 22,312
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 146,411</b>

### Cost Summary for Plumbing with the GFX System

	Direct Labor (inc. Union Dues)	Workmen's Comp, etc. (26%)	O&P (29%) (inc. Tax, Insurance)	Cost per Hour	Total # of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	320	\$ 19,418
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	1280	\$ 74,241
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	320	\$ 16,839
Backhoe	\$ 33.11	\$ 8.61	\$ 9.60	\$ 51.32	60	\$ 3,079
Operator	\$ 33.83	\$ 8.80	\$ 9.81	\$ 52.44	60	\$ 3,146
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 116,724</b>

### Cost Summary for Plumbing with the Sovent System

	Direct Labor (inc. Union Dues)	Workmen's Comp, etc. (26%)	O&P (29%) (inc. Tax, Insurance)	Cost per Hour	Total # of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	240	\$ 14,564
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	960	\$ 55,681
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	240	\$ 12,629
Backhoe	\$ 33.11	\$ 8.61	\$ 9.60	\$ 51.32	60	\$ 3,079
Operator	\$ 33.83	\$ 8.80	\$ 9.81	\$ 52.44	60	\$ 3,146
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 89,100</b>

### Cost Summary for a Combination of Sovent, GFX, and Grooved Fittings

	Direct Labor (inc. Union Dues)	Workmen's Comp, etc. (26%)	O&P (29%) (inc. Tax, Insurance)	Cost per Hour	Total # of Man Hours	Total Cost
Foremen	\$ 39.15	\$ 10.18	\$ 11.35	\$ 60.68	208	\$ 12,622
Journeyman	\$ 37.42	\$ 9.73	\$ 10.85	\$ 58.00	832	\$ 48,257
Apprentice	\$ 33.95	\$ 8.83	\$ 9.85	\$ 52.62	208	\$ 10,945
Backhoe	\$ 33.11	\$ 8.61	\$ 9.60	\$ 51.32	60	\$ 3,079
Operator	\$ 33.83	\$ 8.80	\$ 9.81	\$ 52.44	60	\$ 3,146
					<b>TOTAL DIRECT LABOR:</b>	<b>\$ 78,050</b>



## **Appendix F: Danger Index Calculations for Innovations**

**DANGER INDEX for Prototype Building with Flexible Piping**

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment
Struck Against										8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%			
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%		4.1%
Rubbed ,Abraded or Penetrated				3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (different level)					14.9%	14.9%				
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%		
Bodily Reaction				31.6%				31.6%	31.6%	31.6%
Other (Temperature, Radiation)	9.9%	9.9%								
Incidence Rate (%)	42.0%	42.0%	4.1%	42.1%	39.4%	39.4%	35.6%	46.2%	35.1%	47.2%
Time Exposed (hrs)	56	7	24	10	50	80	60	10	48	20
<b>Danger Index</b>	<b>23.52</b>	<b>2.94</b>	<b>0.984</b>	<b>4.21</b>	<b>19.7</b>	<b>31.52</b>	<b>21.36</b>	<b>4.62</b>	<b>16.848</b>	<b>9.44</b>

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**DANGER INDEX for Prototype Building with Roll Grooved Fittings**

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment
Struck Against										8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%			
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%		4.1%
Rubbed ,Abraded or Penetrated			3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (different level)					14.9%	14.9%				
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%		
Bodily Reaction				31.6%		31.6%		31.6%	31.6%	31.6%
Other (Temperature, Radiation)	9.9%	9.9%								
Incidence Rate (%)	42.0%	42.0%	7.6%	42.1%	39.4%	71.0%	35.6%	46.2%	35.1%	47.2%
Time Exposed (hrs)	56	7	24	10	75	30	60	10	48	20
<b>Danger Index</b>	<b>23.52</b>	<b>2.94</b>	<b>1.824</b>	<b>4.21</b>	<b>29.55</b>	<b>21.3</b>	<b>21.36</b>	<b>4.62</b>	<b>16.848</b>	<b>9.44</b>

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### DANGER INDEX for Prototype Building with GFX System

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment	
Struck Against											8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%				
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%			4.1%
Rubbed ,Abraded or Penetrated			3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	
Fall of Person (different level)					14.9%	14.9%					
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%			
Bodily Reaction				31.6%	31.6%	31.6%		31.6%	31.6%	31.6%	
Other (Temperature, Radiation)	9.9%	9.9%									
Incidence Rate (%)	42.0%	42.0%	7.6%	42.1%	71.0%	71.0%	35.6%	46.2%	35.1%	47.2%	
Time Exposed (hrs)	56	7	20	10	120	30	85	15	48	28	
<b>Danger Index</b>	<b>23.52</b>	<b>2.94</b>	<b>1.52</b>	<b>4.21</b>	<b>85.2</b>	<b>21.3</b>	<b>30.26</b>	<b>6.93</b>	<b>16.848</b>	<b>13.216</b>	<b>206</b>
											<b>DGR INDEX</b>

### DANGER INDEX for Prototype Building with Sovent Aerators

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment	
Struck Against											8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%				
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%			4.1%
Rubbed ,Abraded or Penetrated				3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	
Fall of Person (different level)					14.9%	14.9%					
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%			
Bodily Reaction				31.6%	31.6%	31.6%		31.6%	31.6%	31.6%	
Other (Temperature, Radiation)	9.9%	9.9%									
Incidence Rate (%)	42.0%	42.0%	4.1%	42.1%	71.0%	71.0%	35.6%	46.2%	35.1%	47.2%	
Time Exposed (hrs)	56	7	20	10	120	30	50	10	49	29	
<b>Danger Index</b>	<b>23.52</b>	<b>2.94</b>	<b>0.82</b>	<b>4.21</b>	<b>85.2</b>	<b>21.3</b>	<b>17.8</b>	<b>4.62</b>	<b>17.199</b>	<b>13.688</b>	<b>191</b>
											<b>DGR INDEX</b>

**DANGER INDEX for Prototype Building with Solvent Aerators, GFX, and Grooved Fittings (COMBO)**

	Trench or Backfill Soil for Below Grade	Install Shoring	Prepare Pipe	Connect Pipe (Below Grade)	Connect Pipe (Above Ground)	Install Hangers	Install DWV Stacks	Install Supply Risers	Install Fixtures	Install Equipment
Struck Against										8.0%
Struck By	21.0%	21.0%			21.0%	21.0%	21.0%			
Caught in or Between	4.1%	4.1%	4.1%				4.1%	4.1%		4.1%
Rubbed, Abraded or Penetrated				3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
Fall of Person (different level)					14.9%	14.9%				
Fall of Person (Same level)	7.0%	7.0%		7.0%			7.0%	7.0%		
Bodily Reaction				31.6%		31.6%		31.6%	31.6%	31.6%
Other (Temperature, Radiation)	9.9%	9.9%								
Incidence Rate (%)	42.0%	42.0%	4.1%	42.1%	39.4%	71.0%	35.6%	46.2%	35.1%	47.2%
Time Exposed (hrs)	56	7	30	10	75	30	55	12	40	29
<b>Danger Index</b>	<b>23.52</b>	<b>2.94</b>	<b>1.23</b>	<b>4.21</b>	<b>29.55</b>	<b>21.3</b>	<b>19.58</b>	<b>5.544</b>	<b>14.04</b>	<b>13.688</b>

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